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Prepared at the Leibniz Institute for Neurobiology Magdeburg –
Department of Behavioral Neurology

Master Thesis

The effects of semantic conflict on global feature-based attention

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Beginn der Arbeitszeit:	01.09.2014
Abgabe der Arbeit:	19.05.2015
URN:	urn:nbn:de:gbv:ilm1-2015200091

Declaration

Hereby, I certify that I have prepared this thesis independently under specification of all essential auxiliary means and references.

May 19, 2015

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(Fabian Schadt)

Abstract

Items or features within the focus of attention receive enhanced processing as compared to those outside of it. Following the selection of attended features, the enhanced processing also occurs for these features in the entire visual field in a phenomenon referred to as global feature-based attention (GFBA) (Stoppel et al., 2012). A recent study (Bartsch et al., 2014) showed that relevant color features (color probe) in the unattended visual field elicit enhanced modulations of electromagnetic potentials in the contralateral visual cortex when the color probe matched the color of the attended targets. However, it is unknown whether such enhanced modulations also occur when the feature selection is influenced by semantic incongruencies. Therefore, the aim of this thesis was to analyze the extent to which the neural processing of such a spatially unattended color probe is influenced by the semantic incongruency caused by word/color combinations presented within the focus of attention. To determine the neural correlates of these effects, electroencephalography (EEG) and magnetoencephalography (MEG) were simultaneously recorded in human participants. The task of the participants was, while maintaining fixation, to discriminate the orientation (left/right-tilted) of a colored word within the left attended visual field. Simultaneously, a color probe was shown in the right unattended visual field in the stimulus-relevant colors. For the mismatch of the information present in the attended field (meaning of the word is not matching the color in which it was written), several neural and behavioral interference-related effects were observed. The analysis of the neural correlates of processing of the unattended color probe revealed that colored stimuli without semantic color information elicited enhanced modulations of electromagnetic potentials in the left visual cortex. However, for semantic incongruency of word/color combinations, no significant effects on the processing of the probe were observed. This suggests that either too many resources were bound by the interference effect or that the semantic information was not fully processed in time to have an influence on global feature-based attention.

Zusammenfassung

Objekte oder Merkmale, die innerhalb des räumlichen Aufmerksamkeitsfokus liegen, werden verstärkt wahrgenommen als solche die außerhalb davon liegen. Attendierte Merkmale (z.B. rote Farbe) werden dabei nicht nur im räumlichen Aufmerksamkeitsfokus verstärkt verarbeitet, sondern im gesamten visuellen Feld. Dieses Phänomen wird auch als globale merkmalsbasierte Aufmerksamkeit (GFBA) bezeichnet (Stoppel et al., 2012). Eine kürzlich erschienene Studie (Bartsch et al., 2014) zeigte, dass farblich-relevante Merkmale (Farbkreis), welche außerhalb des räumlichen Aufmerksamkeitsfokus dargestellt wurden, zu einer Sequenz verstärkter elektromagnetischer Potentiale im kontralateralen visuellen Kortex führen, wenn die farblichen Merkmale mit einer zu attendierenden Farbe übereinstimmten. Dabei ist jedoch unbekannt, ob solche verstärkten Modulationen auch auftreten, wenn die Merkmalsselektion durch semantische Inkongruenz beeinflusst wird. In dieser Arbeit soll untersucht werden, inwieweit die neuronale Verarbeitung eines solchen räumlich unattendierten Farbkreises durch semantische Inkongruenz (hervorgerufen durch Farb-Wort-Kombinationen, dargestellt im räumlichen Aufmerksamkeitsfokus) beeinflusst wird. Die Aufgabenstellung der Probanden bestand darin, bei Fokussierung auf ein Fixationskreuz, die Neigung (links/rechts) eines, im linken, attendierten visuellen Feld liegenden, (farbigen) Wortes zu bestimmen. Zeitgleich wurde ein Farbkreis in den stimulus-relevanten Farben im rechten, unattendierten visuellen Feld eingeblendet. Die Messung der Signale erfolgte simultan mittels Elektroenzephalografie (EEG) und Magnetoenzephalographie (MEG). In den Ergebnissen konnten aufgrund der Farb-Wort-Interferenz verschiedene neuronale und Verhaltenseffekte festgestellt werden. Bei der Analyse der neuronalen Korrelate des unattendierten Farbkreises zeigte sich, dass es bei farblichen Stimuli ohne semantische Farb-Bedeutung zu einer Verstärkung der elektromagnetischen Potentiale im linken visuellen Kortex kommt. Dargestellte Farb-Wort-Interferenzen zeigten keinen Einfluss auf die neuronale Verarbeitung des Farbkreises. Dies legt nahe, dass das menschliche Gehirn entweder zu viele Ressourcen zur Verarbeitung der Farb-Wort-Interferenzen benötigt oder dass die semantische Inkongruenz noch nicht vollständig verarbeitet wurde um die globale merkmalsbasierte Aufmerksamkeit zu beeinflussen.

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List of abbreviations

EEG	**E**lectro**e**ncephalo**g**raphy
EOG	**E**lectro**o**culo**g**raphy
EPSP	**E**xcitatory **p**ost**s**ynaptic **p**otential
ERMF	**E**vent-**r**elated **m**agnetic **f**ield
ERP	**E**vent-**r**elated **p**otential
GFBA	**G**lobal **f**eature-**b**ased **a**ttention
HEOG	**H**orizontal **e**lectro**o**culo**g**raphy
IPSP	**I**nhibitory **p**ost**s**ynaptic **p**otential
MEG	**M**agneto**e**ncephalo**g**raphy
RAcc	**R**esponse **acc**uracy
rANOVA	**R**epeated-measures **an**alysis **o**f **va**riance
RT	**R**esponse **t**ime
SNR	**S**ignal-to-**n**oise **r**atio
SQUID	**S**uperconducting **qu**antum **i**nterference **d**evice
VEOG	**V**ertical **e**lectro**o**culo**g**raphy
VF	**V**isual **f**ield

1 Introduction

"Everyone knows what attention is. It is the taking possession by the mind in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought. Focalization, concentration, of consciousness are of its essence. It implies withdrawal from some things in order to deal effectively with others, and is a condition which has a real opposite in the confused, dazed, scatterbrained state which in French is called *distraction*, and *Zerstreutheit* in German."

(William James, Principles of Psychology, 1890)

All the time the human visual system has to deal with countless information, but the human brain seems only to have a limited capacity to process all information. The gathered information is selected passively, which means that only a few stimuli of the whole sensory input are processed (*passive selection*). *Attention* helps to select relevant sensory input, while suppressing irrelevant sensory input (*active selection*) [(Boynton, 2008); (Chun & Wolfe, 2001)]. Specifically, attention enhances the processing of specific sensory input thereby rendering features of that input relevant and available for further processing.

1.1 Aim of the Thesis

Feature-based attention describes a process that occurs when an attended feature within the focus of attention is processed (actively selected) and stimuli outside of the focus, which share the same feature as the attended stimulus (passively selected), may receive enhanced processing. This can be thought of as a form of global attention.

The goal of this study was to find out whether semantic incongruency (within the domain of color information) has an effect on global feature-based attention. To this end, congruent and incongruent word/color combinations were used to determine the influence of semantic incongruency on the neural processing of a color probe presented outside the focus of attention. A congruent word/color combination describes the fact that the font color and its semantic meaning are matching, while for an incongruent word/color combination, the font color and its semantic meaning are non-matching (see chapter 2.3 Stroop-Effect). The task of the participants was to

determine the inclination of the word/color combinations presented in the left visual field (VF) within the focus of attention. Simultaneously, a task-irrelevant color probe was shown in the right, unattended VF (see 3.2 Stimuli and Procedure).

The first aspect to be analyzed was whether the participants would process the task-irrelevant word/color combinations and whether it would affect their behavioral performance on the inclination task. The second and main aspect was to determine whether the responses to the unattended color probe would show any varying electric and magnetic potentials based on the congruent/incongruent configuration of the stimuli within the focus of attention. To determine the neural correlates of these effects, electroencephalography (EEG) and magnetoencephalography (MEG) were used.

1.2 Structure of the Thesis

In the following chapter (chapter 2), some Basic Information about the visual system of the human brain and about the measurement methods EEG and MEG, which were used to measure the experiment are given. Furthermore, the Stroop-effect and information about global feature based attention, which were important for the used stimuli and procedure, are described. Next, the Material and Methods, like information about the participants, the stimuli and procedure as well as the data recording and analysis are described in the chapter 3. In chapter 4, the Results of the experiment are given, followed by a Discussion in chapter 5. The last chapter (chapter 6) gives an Outlook about the upcoming steps as well as a conclusion of this thesis.

2 Basic Information

2.1 Visual Processing

It is known since 1962, that the visual system operates contralaterally which means that a visual stimulus occurring in the left VF gets processed in the right side of the retina of each eye and later on generates neural responses in the right visual cortex [(Hubel & Wiesel, 1962); (Kandel, Schwartz, Jessell, Siegelbaum, & Hudspeth, 2012a)]. Information processed in the right VF likewise generates neural responses in the left visual cortex (Figure 2.1).

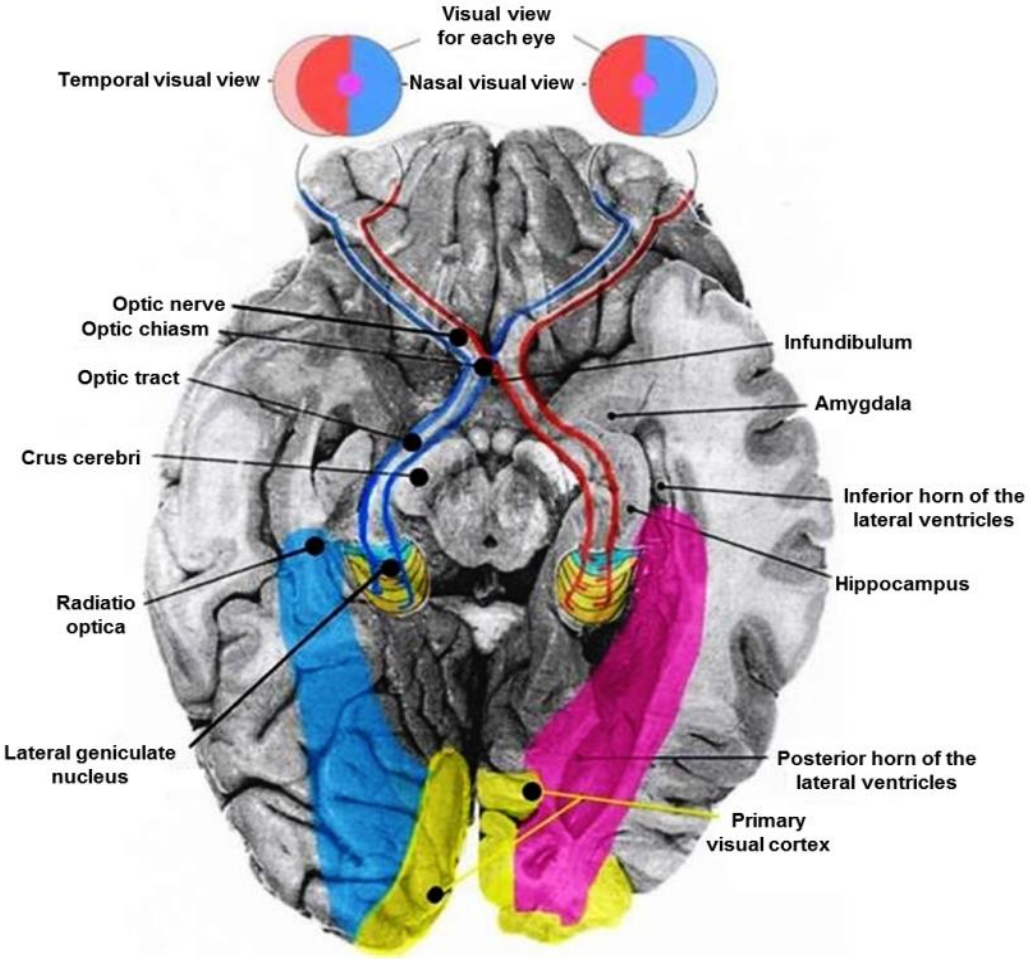


Figure 2.1 - Overview about the process of visualization [Modified from (Gegenfurtner et al.)].

This circumstance will be important for the following study, since the task will be presented in the left VF and therefore processed in the right visual cortex, while the unattended color probe, located in the right global VF, will be processed in the left visual cortex (chapter 3.2). The visual cortex itself is sub-classified in multiple brain

areas: the striate visual cortex *V1* (Hubel & Wiesel, 1962) and the extrastriate visual cortex *V2-V5* (Livingstone & Hubel, 1988) (Zeki, 1993).

If a visual stimulus is processed in the retina of the eye, the information of the stimulus will be divided, abstracted and processed in an ordered structure in the primary visual cortex. From the primary (occipital) cortex, the visual information is usually transmitted through two different pathways in the higher visual cortices: the information is processed first in the occipital cortex (V1) and then either over the dorsal, parietal stream to the parietal cortex or over the ventral, temporal stream to the temporal cortex (Kravitz, Saleem, Baker, Ungerleider, & Mishkin, 2013). Normally, if the stimulus is processed through the parietal stream, information about movements, adjustments of actions and detections of positions are processed. The processing chain is also called "*Where*"-stream [(Mishkin & Ungerleider, 1982); (Goodale & Milner, 1992)]. Damage in high-level dorsal visual cortical regions leads to deficits in the perception of motion, orientation, and in the accuracy of smooth pursuit eye movements (Dragoi). If information about objects, colors, models or shapes is analyzed, the stimulus is usually processed in the ventral stream, which is also called the "*What*"-stream [(Mishkin & Ungerleider, 1982); (Goodale & Milner, 1992)]. Conversely, damage to the ventral visual association cortex gives rise to deficits in high-level visual perception tasks, learning, memory, and attention (Dragoi).

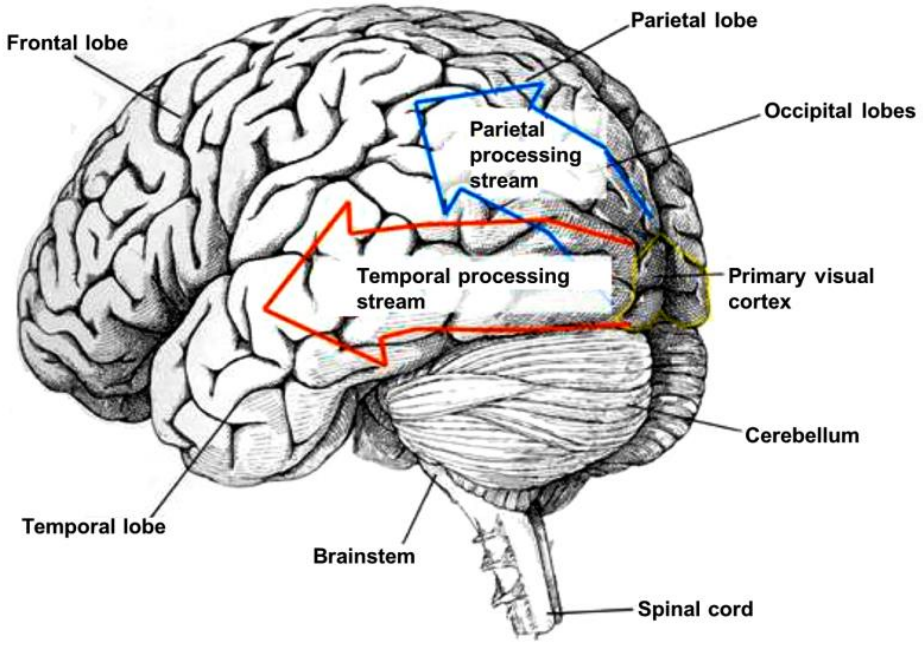


Figure 2.2 - Visual processing streams [Modified from (Gegenfurtner et al.)]: The parietal processing stream (blue) is responsible for the processing of movements, adjustments of actions and detections of positions (Where-stream). The temporal processing stream (red) is responsible for the processing of objects, colors, models or shapes (What-stream).

2.2 Electro-/Magnetoencephalography

EEG is a method which can be used to measure the electrical activity of the brain using electrodes located on the scalp, whereas MEG registers magnetic activity of the brain using external superconducting quantum interference devices (SQUIDs). A combination of these methods, as used in this experiment, allows to simultaneously measure the electric and the magnetic activity of the same neuronal processes.

2.2.1 Origin of electromagnetic Sources

The electromagnetic representation and processing of any information in the brain is achieved through changes in the electric signaling between cells caused by ionic current flows (e.g., K^+, Na^+, Ca^{2+}, Cl^-) between inner and outer membrane of a cells. The information processed is coded in sequences of *action potentials* and transferred over nerve fibers within the nerve system. Usually two types of nerve conductions are differentiated (Figure 2.3):

- *continuous conduction* (forwarding over nerve fiber without myelin sheath)
- *saltatory conduction* (forwarding over nerve fiber with myelin sheath)

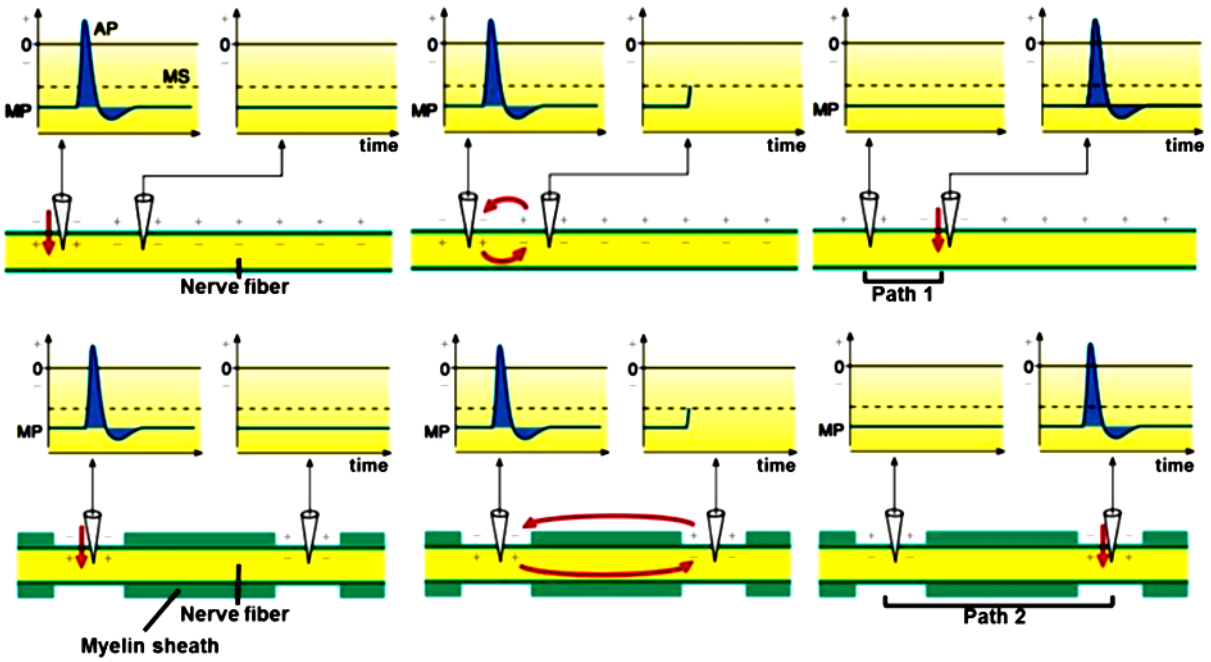


Figure 2.3 - Nerve conductions [Modified from (Suter)] - Continuous conduction (upper graphics) vs. Saltatory conduction (lower graphics): Action potential in the left derivation spot (left); Inflow of cations during extinction (center); Action potential reaches right derivation spot (right).

In continuous conduction, the excitement is transferred to the next neighboring membrane causing a further depolarization, whereas in a saltatory conduction the potential difference has to “jump” from one Ranvier's nodes to the next (the myelin sheath may be compared with an isolator). These “jumps” increase the speed of nerve conduction significantly by using less energy (Suter).

The information of the nerve fibers has to be transmitted over electrical or chemical synapses to other neurons for further processing. Electrical synapses transmit ions via gap junctions, while chemical synapses use second messengers to transmit information from the presynaptic membrane over the synaptic cleft to the postsynaptic membrane. The ionic currents, depending on the direction and composition of the current, create a change of polarity in the postsynaptic structure, which is either excitatory (EPSP – *excitatory postsynaptic potential*) or inhibitory (IPSP – *inhibitory postsynaptic potential*) (Suter). Figure 2.4 gives an overview about the signal processing of a neuron (Kandel, Schwartz, Jessell, Siegelbaum, & Hudspeth, 2012b).

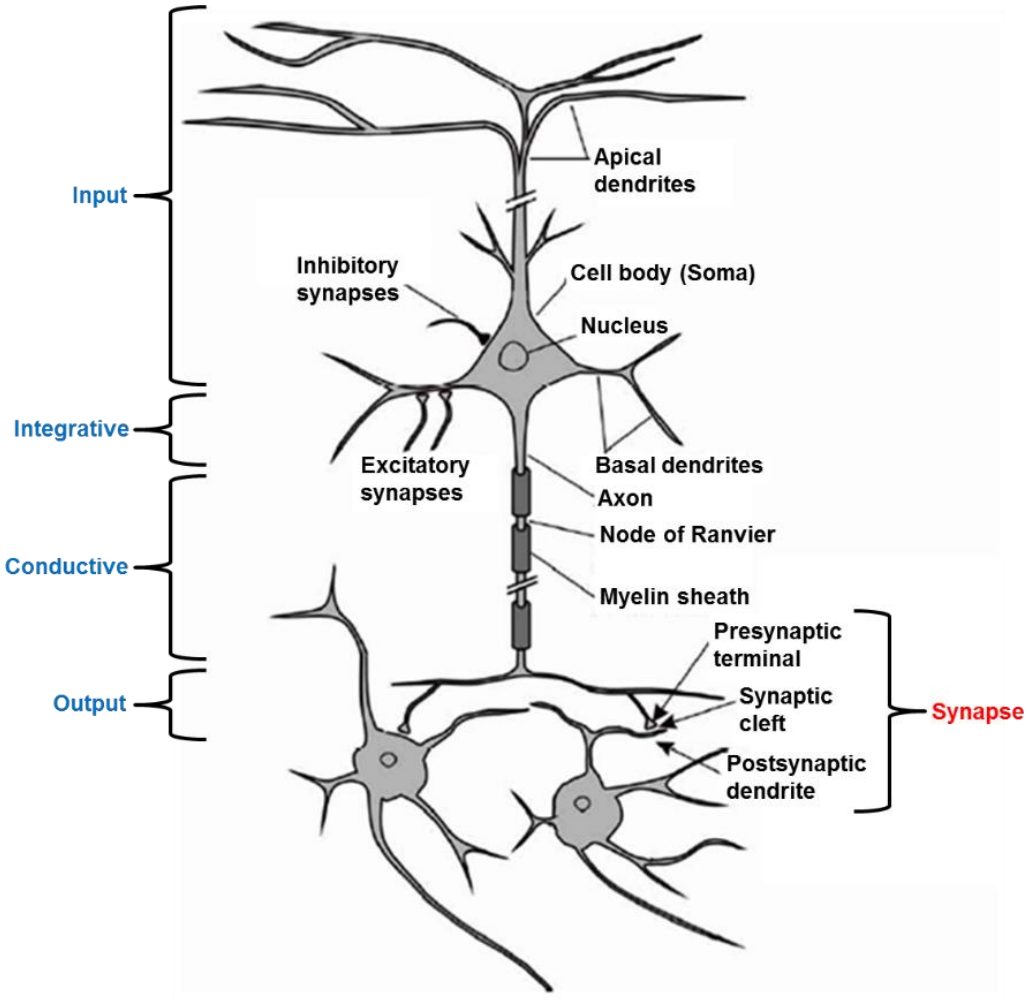


Figure 2.4 - Structure and signal processing of a neuron [Modified from (Kandel et al., 2012b)].

If an IPSP reaches a neuron, the probability for a signal transmission of an action potential to another neuron is quite unlikely but still possible. On the other hand, when an EPSP stimulates a postsynaptic dendrite (or soma) of a neuron, this leads to a local ionic imbalance between inner and outer membrane, called local polarization. Furthermore, this additional charge (positive or negative) caused by the synaptic potential stimulation, results in a potential difference between postsynaptic dendrite and soma. This potential difference creates a current, flowing from the negative to the positive pole, so that the neuron obtains the characteristics of a small dipole. The electric current as well as the ionic imbalance within the neuron generates an electrical field and, perpendicular to the current flow, a magnetic field (Figure 2.5).

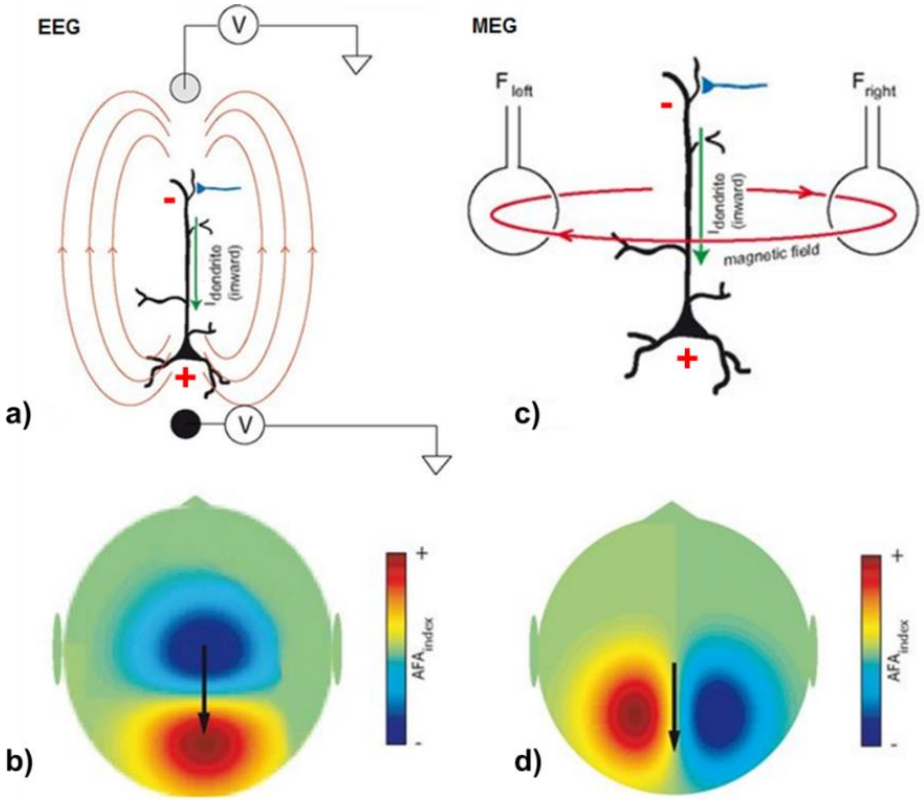


Figure 2.5 - Electromagnetic fields and potentials [Modified from (Mazaheri & Jensen, 2010)]. A synaptic potential stimulation leads to a potential difference between postsynaptic dendrite and soma, creating a current flow from the negative pole to the positive. Each current flow generates a parallel-orientated electrical field (a) and a magnetic field (c), perpendicular to it. Figure (b) and (d) represent the corresponding potentials for the electrical/magnetic field.

2.2.2 Development of Electromagnetic Signals

When the neurons within a population get activated simultaneously, they develop a summed field potential, which can be observed in areas such as the pyramidal cells

in the cortex. Depending on the position, size and orientation of the neural population, the summed field potential can be measured by EEG. The best EEG-signal is developed when the neurons of an assembly are activated simultaneously, when they are parallel to each other and perpendicular to the head surface, and when the potential fields point into the same direction. If the cells are not arranged in this manner, the potential fields may extinguish each other and therefore reduce or eliminate the signal (Figure 2.6). However, since the cortex of the human brain is not just perpendicular to the head surface but convoluted, the signals, which can be measured, are limited. For example, neuron assemblies lying parallel to the head surface cannot be measured using EEG, since the field potentials extinguish each other (Gruber). However, since the magnetic fields are vertically aligned to the electrical fields, MEG can measure the neuron assemblies, which are oriented parallel to the head surface.

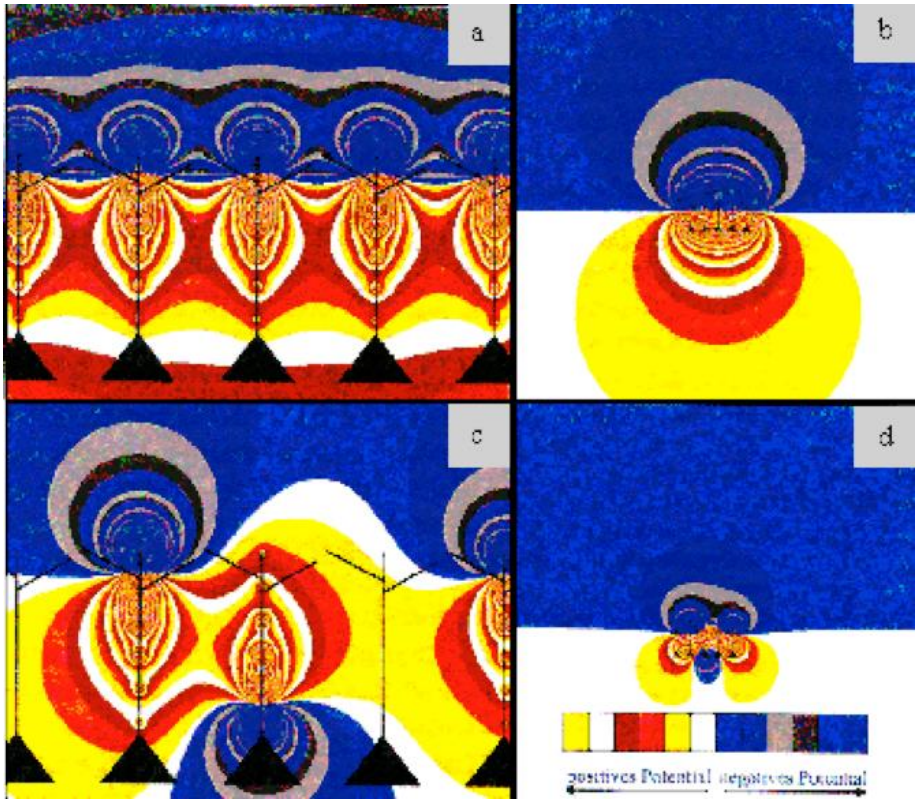


Figure 2.6 - Development of electrical potentials (Gruber). Neuron assemblies of neurons oriented parallel to each other, which get activated simultaneously by a stimulus, develop field potentials (a). These potentials overlap to sum potential field measurable by EEG-electrodes (b). If the neurons do not get fired simultaneously, the potential fields extinguish each other (c) so that no sum potential field can be measured (d).

It is possible to influence the brain's activity using sensory stimulation, e.g., visual or tactile. A change in local field potentials caused by a stimulated event is called an *event-related potential* (ERP) in EEG and an *event-related magnetic field* (ERMF) in

MEG. Sensory stimulation is commonly used in research to localize and analyze specific processing steps of the brain (temporarily and/or spatially).

2.2.3 Measurement of Electromagnetic Signals

Neuronal cells in the cerebral cortex, called pyramidal cells, are lined together in vertical orientation to the cortex making a measurement of a population signal from them possible. If a neural population of pyramidal cells gets stimulated simultaneously, the summed field potential of the neuron population can be measured by EEG-electrodes placed on the scalp. Usually, silver/silver chloride electrodes (electrodes, secondary kind) are used for acquisition. To reduce the impedances and to increase the conductivity it is necessary both to clean the scalp site where the electrode will be placed, as well as to place a conductive paste between the scalp and the electrode. After acquisition of the electrical signals by the electrodes the signals are amplified and digitized. The recorded EEG-signal can be either positive or negative, depending on the orientation of the combined dipoles (Figure 2.7) (Kroger). For recording the magnetic fields in the brain, the head is surrounded by SQUID sensors.

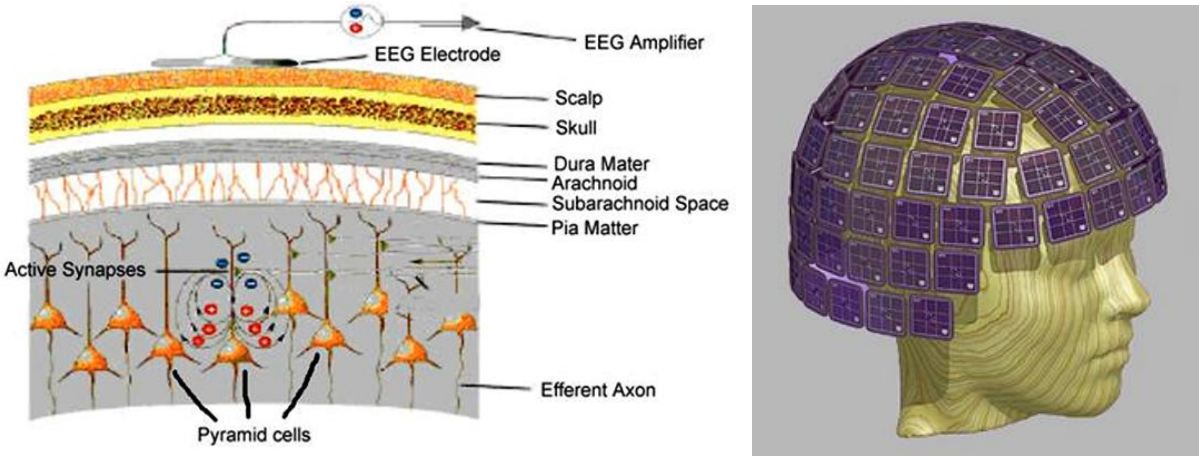


Figure 2.7 - Acquisition of electromagnetic signals using
EEG-electrodes (left): Neurons (pyramid cells) of a neuronal assembly in the cortex activated simultaneously and perpendicular to the head surface develop an electrical signal, which can be measured by EEG-electrodes (Kroger).
MEG-sensors (right): Simultaneously activated neuron populations in the cortex develop a magnetic field, which can measured by SQUID-sensors outside of the head (MEG-System).

While EEG only allows measuring the electric potentials on the head surface, the depth of the signal source makes little difference in the MEG as the magnetic permeability of the brain is more or less overall μ_R=1 (Suter). Since magnetic signals

are not highly affected by the presence of the skull and scalp, the recorded magnetic fields are less distorted than electric fields. Thus, the spatial resolution of the MEG is better than of the EEG.

2.2.4 Artifacts

In order to obtain the best electromagnetic signal, it is necessary to reduce the background noise and to eliminate/reduce all different kind of artifacts, which may influence the quality of the signal. Therefore, several methods were established to improve the quality of the signal. The types of disturbances mentioned here are kept very general and can differ between the methods EEG and MEG, e.g., a technical artifact in EEG can be caused by the electrode, whereas for the MEG a SQUID sensor may be defective. Table 2.1 lists a brief overview of the main groups of disturbances, whether they can be reduced or eliminated, and in which way an enhancement of the signal quality can be reached (Husar, 2010).

Disturbance	Type of removal	Enhancement of the signal quality
Background noise	Elimination/ Reduction	Adaptive filtering
Movements	Elimination/ Reduction	If possible, filtering (e.g., clearing procedure), but typically exclude the epochs containing movement artifacts
Biological artifacts	Elimination/ Reduction	Determination of threshold values
Technical artifacts	Elimination	Exclusion of the epochs containing technical artifacts
Capacitive coupling	Reduction	Removing and/or Shielding of voltage-carrying elements
Inductive coupling	Reduction	Shielding and/or Distancing of sensitive measurement technology from high-powered facilities
Electromagnetic waves	No Elimination/ Shielding possible.	Distancing from commercial transmitters and mobile phones

Table 2.1 - Overview about the main disturbances and their removal in electromagnetic measurements (Husar, 2010).

For this experiment, the mentioned disturbances, which may cause artifacts, were reduced as much as possible, e.g., by measuring in a magnetically shielded (Mu-metal) recording chamber.

2.3 Stroop-Effect

The Stroop-effect, first published by J.R.Stroop in 1935 (Stroop, 1935), describes the behavioral conflict of a color/color-word interference. In J.R.Stroop's first experiment, participants had to read color-words (red, blue, green, brown, and purple) aloud with font colors matching their semantic meaning. When the participants had to read the same list of color-words written in black font color, J.R.Stroop noticed that there was no real difference in the time they needed. However, in the second experiment he figured out that when the participants should name the colors of color-words written in a non-matching font color they needed 74% longer than for naming the colors for a list of solid color squares. As a result, J.R.Stroop hypothesized that reading the meaning of a word requires more attention than naming its font color. Therefore, when processing a discrepancy between semantic meaning of a color-word and its font color the human brain needs enhanced neural processing to generate neural responses, resulting in a behaviorally longer response time when naming/reacting to a non-matching font color of a color-word (see e.g., (MacLeod, 1991)).

In order to examine the Stroop-effect, usually congruent/incongruent stimuli are used. Sometimes a third, neutral stimulus is included (van Maanen, van Rijn, & Borst, 2009):

- *congruent* (color-word and color are matching)
- *incongruent* (color-word and color are non-matching)
- *neutral* (colored word without semantic color reference)

Table 2.2 gives some examples of stimuli, which may elicit the Stroop-effect:

Instruction: Name the **color** for each word listed below

congruent	incongruent	neutral
green, blue, purple, yellow, red, blue	blue, yellow, red, purple, blue, green	house, grass, lion, car, beach, cloud

Table 2.2 - Examples of stimuli, which may elicit a Stroop-effect.

Behaviorally, the Stroop-effect is manifested as the increased response time in the context of incongruent color-word stimuli, decreased response time in the case of congruent color-word stimuli, and an intermediate response time for neutral words [e.g., (van Maanen et al., 2009); (Liotti, Woldorff, Perez, & Mayberg, 2000); (Galer et al., 2014)]. When processing an incongruent color/color-word combination, there is a neuronal conflict caused by the discrepancy of semantic meaning of the color-word and its font color (MacLeod, 1991). Such neuronal conflict influences the behavioral performance leading to a longer response time when naming or responding to the font color of the color-word. In the pilot-test of the Stimuli and Procedure employed in chapter 3.2, this behavioral conflict could also be observed (see chapter 3.3 - Table 3.2).

Since the article of J.R.Stroop, the Stroop-effect has become one of the most well studied behavioral markers of stimulus conflict processing. (Liotti et al., 2000), for example, examined the color/color-word interference effect using ERPs. In one part of their experiment (*Stroop-Verbal Covert*), the participants received the instruction to name the font color of a color-word, presented in the center of their VF, silently in their head. In another part (*Stroop-Manual4*) the participants were instructed to respond as quickly as possible to the ink color of a color-word by pressing the button corresponding to the color (two buttons/hand). There were no neutral stimuli included in the experiment. As result, (Liotti et al., 2000) figured out that the ERP correlates of color-words differ over the scalp between 350-800ms for the responses to incongruent and congruent stimuli. Between 350-500ms, the responses to incongruent stimuli showed a more negative waveform than for the responses to congruent stimuli. For the *Stroop-Verbal Covert* task, the difference was measured in the fronto-central and central regions, while for the *Stroop-Manual4* task, the difference was also found in the parietal region. Later in time, between 500-800ms, this difference inverts in the posterior regions, with the responses to the congruent stimuli being now more negative than the responses to the incongruent stimuli. Figure 2.8 summarizes the results found by (Liotti et al., 2000).

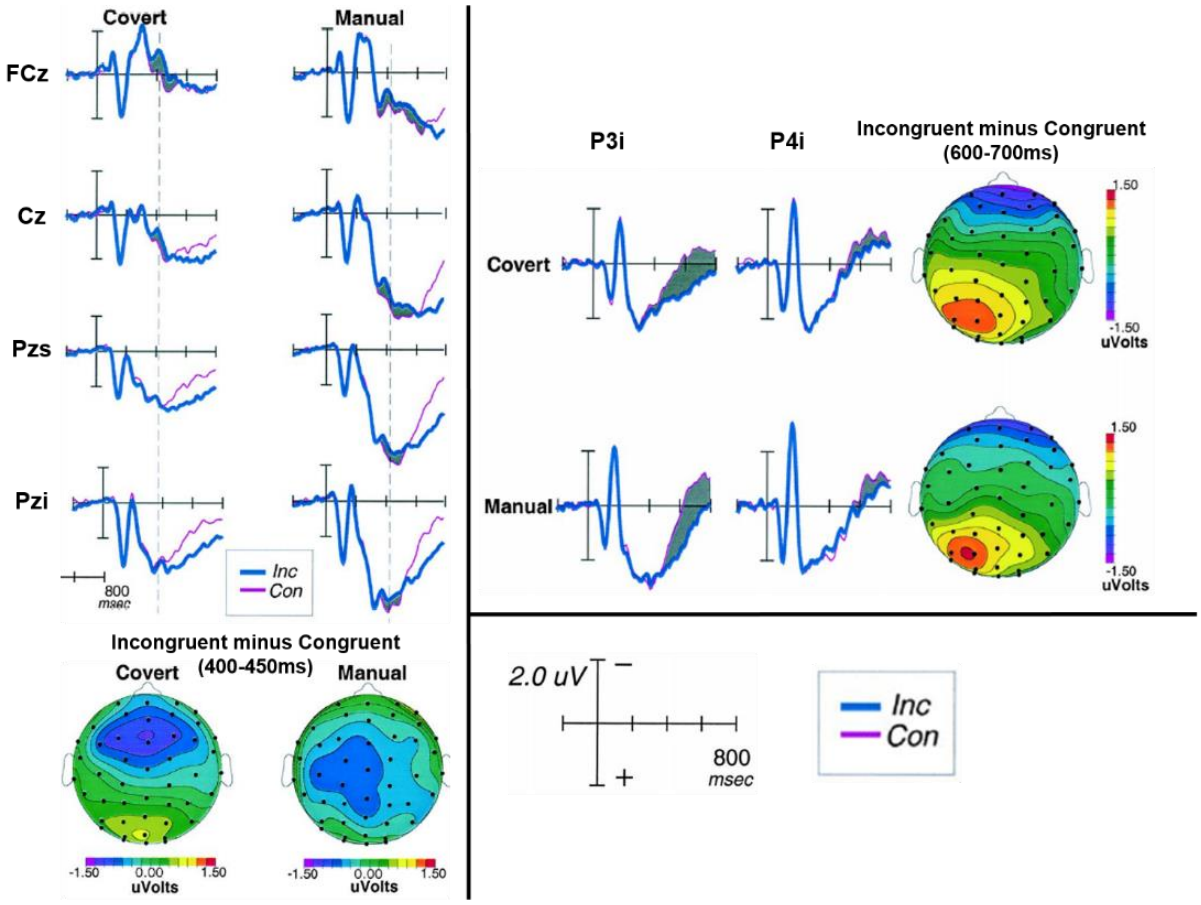


Figure 2.8 - ERPs of a Stroop-Verbal Convert and Stroop-Manual4 task [Modified from (Liotti et al., 2000)]: The waveforms were plotted over a time period of (-200)-800ms after stimulus onset. Additional topomaps show the difference of the incongruent minus congruent condition for specific time windows. For both tasks, there is a more negative waveform for the responses to the incongruent stimuli than for the responses to the congruent stimuli between 350-500ms. While the difference was measured in the EEG-electrode positions FCz and Cz of a standardized 10-10-EEG-cap for the Stroop-Verbal Convert task, the difference appeared also in the parietal regions for the Stroop-Manual4 task. Between 500-800ms, this effect inverts, with the responses to the congruent stimuli being now more negative than the responses to the incongruent stimuli.
A suffix 's' indicates that the electrode was positioned slightly (i.e., within 1–1.5 cm) superior to the indicated standard position, while the suffix 'i' indicates that it was placed inferior to the standard position.

Another study, conducted by (Galer et al., 2014), describes the neural correlates of the Stroop-effect using MEG. Participants indicated the ink color of a presented color-word as quickly as possible via button press (two buttons/hand). In their study, the responses to the incongruent stimuli were significantly more negative than the responses to the congruent stimuli between 380-700ms. Significant differences between the incongruent and congruent waveforms were observed in the middle frontal region between 376-554ms as well as in the temporo-parietal region between 382-582ms (Figure 2.9). (Galer et al., 2014) identified the pre-supplementary motor areas and posterior parietal cortex as playing important roles in the conflict processing reflected by the Stroop-effect.

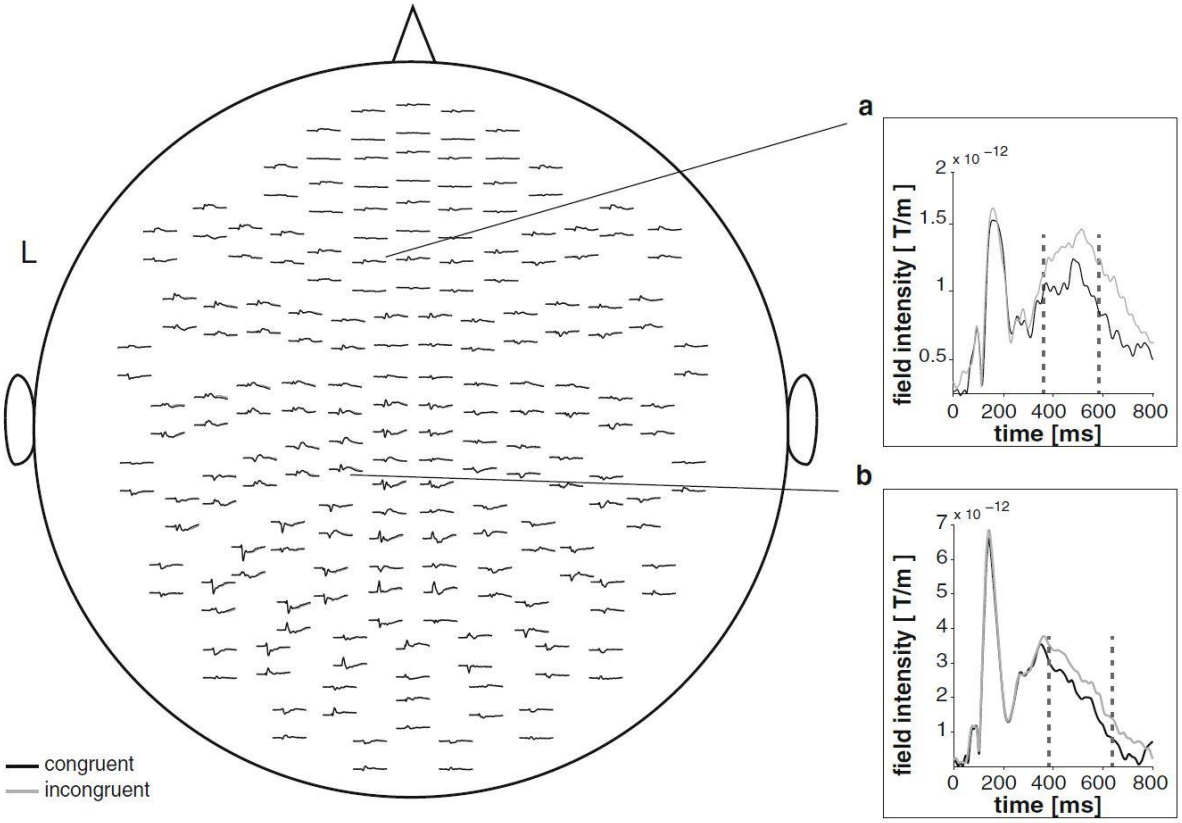


Figure 2.9 - EMFs of a Stroop-task (Galer et al., 2014): The congruent EMFs (dark line) and incongruent EMFs (grey line) of a Stroop-task were presented as spatial distribution of an average over 12 participants. In the middle frontal region between 376-554ms (a) as well as in the temporo-parietal region between 382-582ms (b) significant differences between the responses to the incongruent and the responses to the congruent stimuli have been found.

2.4 Global Feature-Based Attention

One well-studied distinction in the field of spatial attention is that between *endogenous* and *exogenous* attention. Endogenous attention, also known as *top-down* goal-driven attention, is directed voluntary or when specific information is given in advance to the participant, e.g., the task-relevant object will appear in the right VF. In contrast, exogenous attention, also referred to *bottom-up* stimulus-driven attention, happens involuntarily often caused by a sudden change, flash or sound. Generally, almost every attention-driven visual process is determined by interactions between a *bottom-up* input and a *top-down* perceptual set (Chun & Wolfe, 2001). In feature-based attention, features within the VF are detected and processed in a spatially global way. That is, attending to a feature somewhere in a visual scene automatically entails the selection of that feature throughout the whole VF and thus even at spatially unattended locations. Recent studies on *global feature-based*

attention (GBFA) have shown that the processing of features like color [e.g., (Zhang & Luck, 2009)], motion [e.g., (Stoppel et al., 2012)] or orientation [e.g., (Bondarenko et al., 2012)] presented outside the VF is enhanced when these features share properties with an attended feature.

In the MEG study of (Bartsch et al., 2014), the performed experiment was based on *global color-based attention*. Participants had to make a color/shape discrimination in the left VF, while task-irrelevant color probes were shown in the right unattended VF. The participants attended to a bicolored circle consisting of two differently-colored half circles. The task for the participants was to determine whether the relevant target-color was presented in the left or the right half circle by pressing a button. The simultaneously presented irrelevant color probes in the right VF could either match or not match the attended color. By analyzing the response of the irrelevant color probe with the defined target-color of the attended discrimination task, (Bartsch et al., 2014) discovered a sequence of modulations in extrastriate cortex reflecting global color selection. Independent from color competition in the focus of attention, these modulations manifested as an initial phase in the lateral occipital complex followed by a later phase in the retinotopic areas V3/V4. In addition, (Bartsch et al., 2014) figured out that task-relevant colors presented as irrelevant color probe, but absent in the focus of attention, showed early parts of the modulations. However, when the participants were instructed to simply detect the onset of the target without color/shape discrimination, no modulations in the extrastriate visual cortex were observed.

Following on from this study, the influence of congruency between word/color associations on global feature-based attention within the domain of color information should be examined. For this, the color discrimination task of (Bartsch et al., 2014) was exchanged by an inclination discrimination task using tilted (color-)words, which were able to elicit a color/color-word interference (see also chapter 3.2). Since the task-irrelevant word/color combinations were presented within the attended global VF, it was possible that the conflict present at the level of the stimulus might still influence behavioral performance, although the semantic meaning of the words as well as the presented colors were irrelevant to perform the inclination discrimination task. However, it is still unknown whether such an indirectly attended interference-related conflict may affect the selection of color features. Therefore, the main aspect to be analyzed was the extent to which a spatially unattended color

probe was influenced by the semantic incongruency caused by word/color combinations presented within the focus of attention.

Based on the findings of (Bartsch et al., 2014), there should be enhanced neural processing of the color probe when its color matches that of the stimuli. However, the effect would likely be smaller than in (Bartsch et al., 2014), since the participants were not instructed to pay attention to a specific color. For congruent word/color combinations, the congruency should lead to enhanced neural processing of a color probe matching the color of the congruent stimuli, while non-matching color probes would not be attended and therefore would not show this effect. A processed color of a neutral word (without color-related semantic content) would probably also enhance the neural processing of the color probe but less so than a congruent stimulus. Again, a non-matching color probe would not cause such an effect since the probe would not be attended. Incongruent word/color combinations could influence the neural processing of the color probe in three different ways. First, it is possible that there would be no effect in the neural processing of the color probe at all since too much attention is needed to process the color/color-word interference itself. Second, color-matching stimuli with non-matching semantic content would lead to enhanced neural processing of the color probe, which would decrease later in time when the non-matching semantic meaning of the word is processed. Third, stimuli with matching semantic meaning but non-matching color would show no early effects on the processing of the color probe. However, when processing the matching semantic meaning of the word later in time, the neural processing of the unattended color probe could be enhanced. Based on the unrelated processing of semantic meaning of a word and color, the third possibility seems quite unlikely.

A main difference to (Bartsch et al., 2014) and to other studies with the aspect of GFBA was that no information about task-relevant features of interest (e.g., color) were given in advance and therefore they were not directly attended by the participants. Here, the information given about the experimental task (determine the inclination of a presented word) was completely irrelevant to the experimental manipulation of interest (word/color combinations and its influence in the neural processing of the unattended color probe).

3 Material and Methods

3.1 Participants

Before measuring electrophysiological data, 22 paid participants (13 males, 6€/h for participation, mean age 25.8) were behaviorally tested in a darkened chamber in order to find out whether the conflicting stimuli elicit a Stroop-effect when the conflicting feature is not directly attended. In the main experiment, 38 paid participants (22 males, 6€/h for participation, mean age 26.1) were measured with EEG/MEG recordings. Twenty participants (9 males, mean age 26.2) were used for this study, while 18 participants had to be excluded because of low behavioral performance (Response Accuracy less than 0.75), artifacts, or technical issues. All participants for behavioral pilot session and main experiment measurement were healthy, right-handed, with normal or corrected-to-normal vision and all were native German speakers.

3.2 Stimuli and Procedure

3.2.1 Experimental Design

As seen in Figure 3.1, a fixation-cross was superimposed on the center of each stimulus array. The background color for the experiment was set to gray (RGB: 120; 120; 120).

In the left attended VF, a colored word was presented in each trial. All words were written in the font “Arial” and each letter had a different font size (originally: 12, 16, 20, 24; in random order with no repeated font sizes within word). This gave a total of 24 possible word variations, from which stimuli were randomly selected. On a given trial, the stimulus presented was randomly selected from the 24 possible word variations. All word constructs were vertically centered, tilted by 1° to the left/right side and cut into sizes of 510×210 pixels. In order to avoid that the stimuli were seen as simple objects by creating imaginary lines, the different sized letters were

vertically centered. In light of research showing that viewers can detect tilt angle differences at a magnitude of 0.5° (Vogels & Orban, 1985), the current study employed tilt angle differences of 1° to ensure adequate performance. The stimulus words used were *GELB* (Ger. for *yellow*), *GRÜN* (Ger. for *green*) or *GOLF* (Ger. for *golf*) and the stimulus colors were, matching to the semantic meaning of the words, presented in yellow, green or (neutral) white. Advantages of the colors yellow and green were that they showed similar ERPs in attentional deployment in the electrodes PO7/PO8 (Pomerleau, Fortier-Gauthier, Corriveau, Dell'Acqua, & Jolicoeur, 2014), that they are able to elicit the Stroop-effect, as well as that these color-words are visually similar in German orthographics. The word *GOLF* was chosen randomly as neutral word since, like the color-words, it consists of four letters and it begins with 'G'.

In the right unattended VF, a full circle in a uniform color was presented. This circle was used as color probe and appeared randomized in the mentioned colors (yellow, green, white). The responses of these color probes in the left hemisphere of the brain were later analyzed in order to find out whether congruent and incongruent word/color combinations have any influence in the neural processing of the color probe.

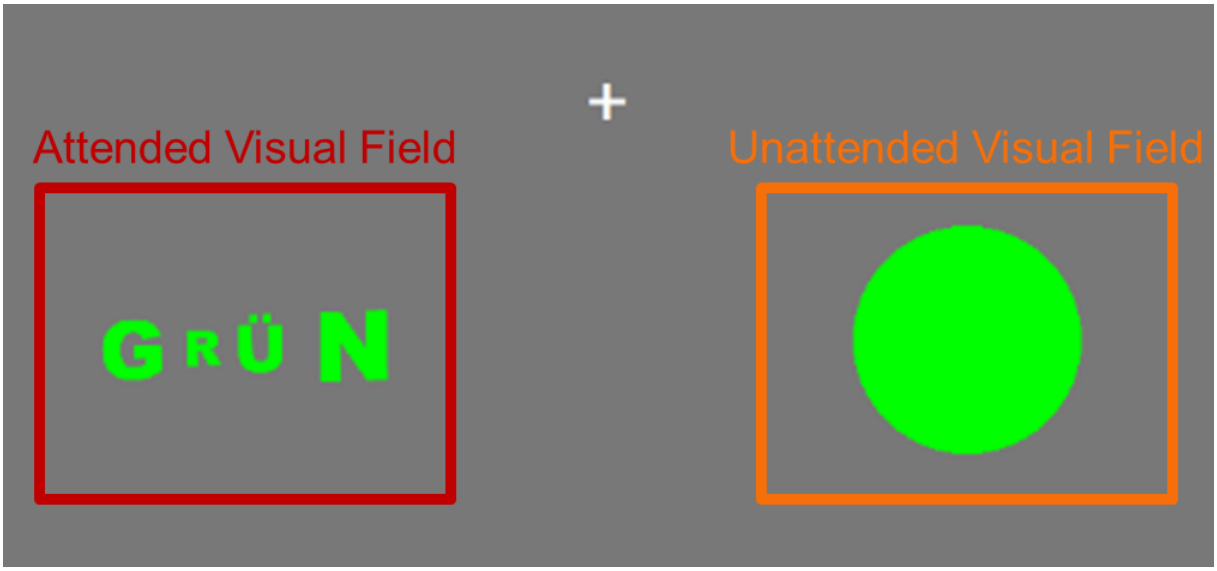


Figure 3.1 - Experimental design. A color/(color-)word combination was presented at a fixed position in the attended left VF, while a uniformly colored circle (color probe) was shown in the unattended right VF at the same time.

As in (Bartsch et al., 2014), both centers of the word, as well as of the probe, were placed 3.1° below and 4.9° to the left and right from the fixation-cross, while the circle subtended a diameter of 3.1° (visual angle).

3.2.2 Experimental Task

The task of the participants was, while maintaining fixation on the center-cross, to determine whether the word presented in the attended left VF was either tilted to the left or to the right side. For differentiation, two different buttons could be pressed by the participants with the right hand: index finger if the word was tilted to the left side, middle finger if the word was tilted to the right side. Each stimulus trial was shown for 900ms with subsequent trials presented with a randomly varying *stimulus onset asynchrony* between 1000 and 1400ms.

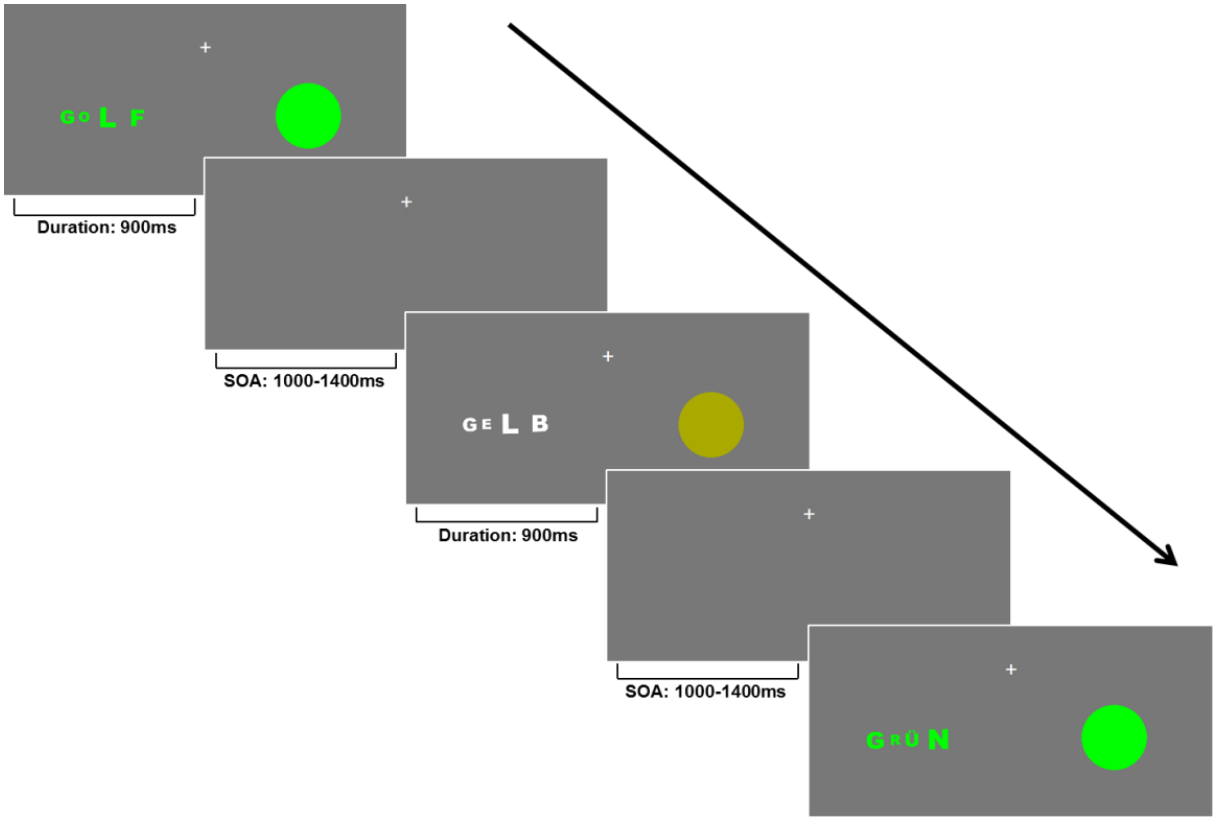


Figure 3.2 - Experimental task. The task of the participants was to determine the inclination of the presented word (here: right, left, left), while maintaining fixation on the center-cross. Each stimulus trial was shown for 900ms, with a randomly varying stimulus onset asynchrony (SOA) between 1000-1400ms (jittered) after each stimulus trial.

3.2.3 Experimental Session

The Experimental Design allowed a total number of 54 different possibilities of trial types (see Table 3.1).

	Possibilities
Inclinations	2 (left tilted, right tilted)
Stimuli words	3 (GOLF, GELB, GRÜN)
Stimuli colors	3 (white, yellow, green)
Probe colors	3 (white, yellow, green)
In total	**54 Trial types**

Table 3.1 - Total number of trial types.

All participants did ten experimental blocks per session with $3 \times 54 = 162$ trials per block each. In total, 1620 trials were shown in a randomly order, of which 600 trials contained any color information (semantic or color) matching the color of the probe (trials including white as probe color were excluded). Of these 600 trials, 120 trials had congruent stimuli [(Stimuli-Word: *GELB*, Stimuli-Color: yellow, Probe-Color: yellow); (Stimuli-Word: *GRÜN*, Stimuli-Color: green, Probe-Color: green)], 240 trials had incongruent stimuli [(Stimuli-Word: *GELB*, Stimuli-Color: green, Probe-Color: yellow); (Stimuli-Word: *GELB*, Stimuli-Color: green, Probe-Color: green); (Stimuli-Word: *GRÜN*, Stimuli-Color: yellow, Probe-Color: green); (Stimuli-Word: *GRÜN*, Stimuli-Color: yellow, Probe-Color: yellow)]. The remaining 240 trials contained either the color-words *GELB* or *GRÜN* written in a white font [(Stimuli-Word: *GELB*, Stimuli-Color: white, Probe-Color: yellow); (Stimuli-Word: *GRÜN*, Stimuli-Color: white, Probe-Color: green)] or the neutral word *GOLF* written in a yellow or green font color [(Stimuli-Word: *GOLF*, Stimuli-Color: yellow, Probe-Color: yellow); (Stimuli-Word: *GOLF*, Stimuli-Color: green, Probe-Color: green)].

3.3 Pilot-Test and Color-Adjustment

In advance, 22 participants tested the Stimuli and Procedure to figure out whether the mismatch of the information present in the stimulus (meaning of the word vs. the ink color in which it was written) could elicit a similar behavioral interference-related effect to that elicited by a Stroop-task, even though the current experiment was

not a Stroop-task. Therefore, the behavioral *response accuracy* (RAcc) and *response time* (RT) were analyzed. On average, the RAcc for the *Hit-Rate* was about 0.779 (± 0.028), while the RT was about 667ms (± 20ms). Since the focus was on the Stroop-effect, the stimuli for congruency (congruent, incongruent, neutral) were analyzed independently from the color of the probe.

First, repeated measures analyses of variance (rANOVA) with the factors congruent, incongruent and neutral were performed for the behavioral RAcc and RT. These analyses revealed a significant effect for RT ($F_{2,42}$ = 7.852; p = 0.001), while no significant effect was found for RAcc ($F_{2,42}$ = 2.303; p = 0.113). Post-hoc planned comparisons showed that the significant effect in RT was driven by the responses to the congruent stimuli being significantly faster than the responses to the incongruent stimuli (t_{21} = 3.967, p = 0.001). Furthermore, two trends were found for the responses to the congruent and the neutral stimuli as well as for the responses to the incongruent and the neutral stimuli [congruent: RT = 659ms; incongruent: RT = 672ms; neutral: RT = 665ms; (congruent-neutral: t_{21} = 1.906, p = 0.070); (incongruent-neutral: t_{21} = 2.049, p = 0.053)]. The behavioral RT data confirmed that the stimuli elicited a behavioral interference-related effect similar to that of a Stroop-task. Summarized information about the RAcc and RT is given in Table 3.2.

22 Participants	**Average**	**Congruent**	**Incongruent**	**Neutral**
Response Accuracy	0.779	0.787	0.784	0.768
Root mean square deviation	0.028	0.031	0.028	0.028
Response time (ms)	667	659	672	665
Root mean square deviation (ms)	20	20	20	20

Table 3.2 - Response accuracy and response time for the pilot-test (independent from the probe color).

In order to equate the luminance, a flicker-test based on heterochromatic flicker photometry was performed [(Demarco, Brigell, & Gordon, 1997); (Lee, Martin, & Valberg, 1988)]. In this flicker-test, the colors yellow and green were sinusoidally alternated with a frequency of 60Hz until their relative intensities adjusted similarity and the flicker were minimized. Five healthy, independent participants performed the flicker-test in the magnetically shielded chamber (see chapter 3.4). Since there was a larger effect for the color green than for yellow, green was used as base color (RGB: 0, 255, 0). As result, the RGB values for yellow were adjusted from (255; 255; 0) to (169; 169; 0) for the measurement.

3.4 Data Recording

EEG and MEG were recorded simultaneously in a magnetically shielded (Mu-metal) recording chamber. For both, the sample rate was 254Hz. An online low-pass filter with DC-to-50Hz was used to diminish slow signal drift and high frequency noise.

For recording the EEG, a 32-electrode cap (Ag/AgCl electrodes; Falk Minow Services) and an EPA-6 amplifier system (Sensorium) were used, while a 248-channel BTI Magnes whole-head magnetometer system (4-D Neuroimaging Magnes WH 3600) was used to record the MEG. An online-based reference environmental coil system, described by (Robinson, 1989), was applied to reduce environmental magnetic artifacts. References of the recorded EEG signal were the right mastoid and the data were re-referenced offline to the algebraic mean of the left and right mastoid. FPz was used as ground electrode. All impedances were less than 5kOhm. To monitor eye-movements, an *electro-oculogram* (EOG) was recorded with bipolar montages of electrodes at the left and right outer canthies (HEOG), as well as a unipolar electrode below the right eye (VEOG). A 3Space Fastrak System (Polhemus, Colchester, VT, USA) was used to co-register anatomical and MEG data by digitizing the individual anatomical landmarks (nasion, caesion, inion, left and right preauricular point), the 5 localizer coils placed at standardized positions in the EEG cap (Easycap, Herrsching, Germany) as well as the positions of all 32 electrode positions. Furthermore the participant were monitored during the experiment by a custom-made zoom lens infrared camera system.

The trials of the experiment were displayed over a DepthQ HDs3D-1 projector (Lightspeed Design, Inc., Bellevue, WA, USA) into the chamber using the program Presentation (Neurobehavioral Systems, Inc., Version 14.3). Size of the screen was 46*57cm^2, while the distance between screen and participant was 1m.

The software Magnetic Source Imaging (Biomagnetic Technologies Inc., Version 1.4) was used to do primary analysis like epoching and averaging of the EEG and MEG data. For repositioning the MEG data, the multimodal neuroimaging software Curry 7.0 (Compumedics Neuroscan, Compumedics USA, Ltd., Charlotte, NC, USA) was used. IBM's statistic-software SPSS (Version 16.0) was used to analyze the behavioral data.

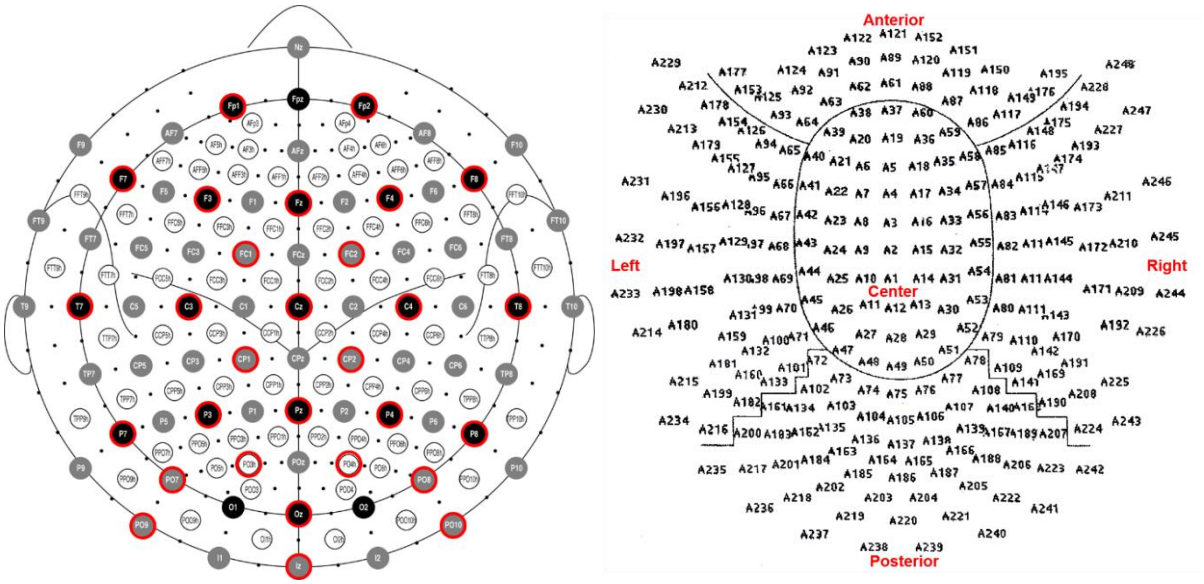


Figure 3.3 - Sensor distribution of the used EEG (left) and of the used MEG (right) [EEG modified from (Oostenveld & Praamstra, 2001)]. Electrode positions, which were derived in the experiment, are circled in red color (left).

3.5 Data Analysis

3.5.1 Behavioral and EEG/MEG Analysis

First, the raw data were separated into epochs, with a time range of (-200) to 1200ms for each stimulus, excluding incorrect and missed responses. To calculate the ERPs and ERMFs from the data, the epochs containing the same trial types were averaged and combined to a *bin*. A pre-stimulus baseline interval of 200ms was used for plotting and statistics. Offline artifact rejection was applied to the epochs within each *bin*. Since the data for each participant contained artifacts of different sizes (e.g., eye blinks of differing magnitude), the thresholds for artifact rejection were set in an iterative manner individually for each participant until the major artifacts were removed of the data. Specifically, on average, 11.30% (± 1.50%) of the epochs were rejected in the EEG data, and 8.67% (± 1.36%) of the epochs were rejected in the MEG data (for detailed information, see Attachment 1). The thresholds were ranging between 65 to 120µV for the EEG (mean: 93.75µV) and between 2.6 to 3.6pT for the MEG (mean: 3.2pT). First, left and right tilted words including the same experimental condition were collapsed for each participant. Then, for further analysis, trials sharing

the same features (e.g., congruent word/color combinations) were collapsed and compared with other collapsed trials (e.g., incongruent word/color combinations).

In order to figure out significant effects, statistical analyses were performed on the behavioral and the ERP/ERMF data by determining repeated-measures analyses of variance (rANOVA). For the behavioral response accuracy and response time, 3x3x3 rANOVAs were employed for the factors of *Stim_Word* (*GOLF*, *GELB*, *GRÜN*), *Stim_Color* (white, yellow, green) and *Probe_Color* (white, yellow, green). Significant differences and interactions were further analyzed by performing post-hoc planned comparisons. For the ERP/ERMF data, the rANOVAs were employed on the mean amplitude values. Significance was considered to be less than 0.05 for all analyses and for the rANOVAs the results were adjusted using the Greenhouse-Geisser method.

3.5.2 Co-registration of Anatomical and MEG Data

As mentioned in chapter 3.4, in advance of each measurement, five individual landmarks (nasion, caesion, inion, left and right preauricular point), five spatially distributed coils at standardized positions in the EEG cap as well as all 32 electrode positions were digitized for each participant. Since head position may vary across subjects during a recording session, the data had to be repositioned such that all subjects had data originating from the same locations within the MEG helmet. The five individual sensor positions of the anatomical landmarks formed the basis to co-register the recorded MEG data with a reference sensor set (selected from 1500 MEG measurements) of the most canonical position relative to the anatomical landmarks (A121, A1, A220, A214, A226).

In order to reposition the data, the individual field distributions of each data set (matrixes, which contain the weights of all dipoles) were first projected from the sensor- into the source-space of the realistic anatomical MNI brain of the Neurological Institute of Montreal, CA. The MNI brain is an averaged ICBM-152 template (152 T1-weighted stereotaxic volumes), which can be used as neuroimaging tool. The settings used to get the lead fields were *BEM Liquor 7mm* as volume conductor (derived by grey matter layer and 3D-surface segmentations of the cerebrospinal fluid space) (Fuchs et al., 1998), *minimum norm least square* as

current density (stronger bias towards superficial sources) (Fuchs, Wagner, Kohler, & Wischmann, 1999) and *cortex no cerebellum* as source location. The BEM Liquor 7mm boundary element model is built on the intracranial space containing the cerebro spinar liquid. In the minimum norm least square method, source density estimates (SDEs), a distribution of currents over the cortical surface based on their weighted measurement errors (pseudo-F-values), are used to determine the current estimates at each source location (Stoppel et al., 2012). In order to avoid neural motor activity, the cerebellum was excluded in the analysis.

The data were then back-transformed from the source-space into the sensor-space (forward solution), and the (varied) sensor positions of each individual field distributions were aligned with the field distributions of the reference sensor set. Specifically, the sensor positions of the 20 individual data sets were repositioned to the reference sensor positions, allowing the computation of a *grand average data* set.

4 Results

4.1 Behavioral Data

4.1.1 Response Accuracy

The grand averaged response accuracy (RAcc) for the congruent, incongruent and neutral stimuli is given in Table 4.1.

20 Participants	Average	Congruent	Incongruent	Neutral
Response Accuracy	0.794	0.803	0.799	0.782
Root mean square deviation	0.010	0.010	0.011	0.012

Table 4.1 - Grand averaged response accuracy (independent from the probe color).

A 3x3x3 repeated measures analysis of variance (rANOVA) with the factors of *Stim_Word* (*GOLF*, *GELB*, *GRÜN*), *Stim_Color* (white, yellow, green) and *Probe_Color* (white, yellow, green) was performed for the behavioral RAcc data. This analysis revealed a significant main effect for the factors *Stim_Word* ($F_{2,38}$ = 5.073, p = 0.017) and *Stim_Color* ($F_{2,38}$ = 5.531, p = 0.010), while no significant main effect of the factor *Probe_Color* was observed ($F_{2,38}$ = 1.878, p = 0.171). Further a significant interaction was observed between *Stim_Word*Stim_Color* ($F_{4,76}$ = 3.102, p = 0.024) and a trending interaction for *Stim_Color*Probe_Color* ($F_{4,76}$ = 2.603, p = 0.050). There were no significant interactions between *Stim_Word*Probe_Color* ($F_{4,76}$ = 0.631, p = 0.590) and *Stim_Word*Stim_Color*Probe_Color* ($F_{8,152}$ = 1.292, p = 0.276). Table 4.2 provides a summary of these results.

Main effects / Interactions	F-Value	Significance
$Stim\_Word_{RAcc}$	$F_{2,38}$ = 5.073	p = 0.017*
$Stim\_Color_{RAcc}$	$F_{2,38}$ = 5.531	p = 0.010*
$Probe\_Color_{RAcc}$	$F_{2,38}$ = 1.878	p = 0.171
$Stim\_Word_{RAcc}$* $Stim\_Color_{RAcc}$	$F_{4,76}$ = 3.102	p = 0.024*
$Stim\_Color_{RAcc}$* $Probe\_Color_{RAcc}$	$F_{4,76}$ = 2.603	p = 0.050˜
$Stim\_Word_{RAcc}$* $Probe\_Color_{RAcc}$	$F_{4,76}$ = 0.631	p = 0.590
$Stim\_Word_{RAcc}$* $Stim\_Color_{RAcc}$* $Probe\_Color_{RAcc}$	$F_{8,152}$ = 1.292	p = 0.276

Table 4.2 - Significant effects and interactions for RAcc revealed by the rANOVA.

Following the first rANOVA, post-hoc planned comparisons were performed for all significant main effects and interactions. The main effect of *Stim_Word* was driven by the factors *GELB* and *GRÜN* both having significantly higher RAcc than the factor *GOLF* [*GOLF*: RAcc = 0.781; *GELB*: RAcc = 0.801; *GRÜN*: RAcc = 0.799; (*GOLF-GELB*: $t_{19} = 2.816$, $p = 0.011$); (*GOLF-GRÜN*: $t_{19} = 2.517$, $p = 0.021$)]. For the main effect of *Stim_Color*, the participants showed a significantly lower RAcc for yellow than for white or green targets [white: RAcc = 0.800; yellow: RAcc = 0.782; green: RAcc = 0.801; (yellow-white: $t_{19} = 3.407$, $p = 0.003$); (yellow-green: $t_{19} = 2.662$, $p = 0.015$)]. The post-hoc planned comparisons revealed for the significant interaction between *Stim_Word*Stim_Color* that the participants showed a (marginally) significant lower RAcc for the comparisons [(GOLF* white): RAcc = 0.776], [(GOLF* yellow): RAcc = 0.776], [(GELB* yellow): RAcc = 0.792] and [(GRÜN* yellow): RAcc = 0.779] than for the comparisons [(GELB* white): RAcc = 0.817], [(GRÜN* white): RAcc = 0.807] and [(GRÜN* green): RAcc = 0.813], while the comparisons of the significant interaction between *Stim_Color*Probe_Color* were mainly driven by the low RAcc of the comparisons [(yellow* white): RAcc = 0.778] and [(yellow* yellow): RAcc = 0.776] and the high RAcc of the comparisons [(white* green): RAcc = 0.806] and [(green* white): RAcc = 0.817]. For detailed information about the comparisons, which were responsible for the significant differences, see Table 4.3.

Main effects/ Interactions	**Value 1**	**Value 2**	**t-Value**	**Significance**
$Stim\_Word_{RAcc}$	GOLF RAcc = 0.781	GELB RAcc = 0.801	$t_{19} = 2.816$	$p = 0.011$*
	GOLF RAcc = 0.781	GRÜN RAcc = 0.799	$t_{19} = 2.517$	$p = 0.021$*
$Stim\_Color_{RAcc}$	yellow RAcc = 0.782	white RAcc = 0.800	$t_{19} = 3.407$	$p = 0.003$*
	yellow RAcc = 0.782	green RAcc = 0.801	$t_{19} = 2.662$	$p = 0.015$*
$Stim\_Word_{RAcc}$* $Stim\_Color_{RAcc}$	GOLF* white RAcc = 0.776	GELB* white RAcc = 0.817	$t_{19} = 3.538$	$p = 0.002$*
	GOLF* white RAcc = 0.776	GRÜN* white RAcc = 0.807	$t_{19} = 2.473$	$p = 0.023$*
	GOLF* white RAcc = 0.776	GRÜN* green RAcc = 0.813	$t_{19} = 3.022$	$p = 0.007$*

	GOLF* yellow RAcc = 0.776	GELB* white RAcc = 0.817	t_{19} = 4.224	p = 0.000*
	GOLF* yellow RAcc = 0.776	GRÜN* white RAcc = 0.807	t_{19} = 2.603	p = 0.017*
	GOLF* yellow RAcc = 0.776	GRÜN* green RAcc = 0.813	t_{19} = 3.174	p = 0.005*
	GELB* yellow RAcc = 0.792	GELB* white RAcc = 0.817	t_{19} = 2.989	p = 0.008*
	GELB* yellow RAcc = 0.792	GRÜN* white RAcc = 0.807	t_{19} = 2.094	p = 0.050˜
	GRÜN* yellow RAcc = 0.779	GELB* white RAcc = 0.817	t_{19} = 6.277	p = 0.000*
	GRÜN* yellow RAcc = 0.779	GRÜN* white RAcc = 0.807	t_{19} = 3.501	p = 0.002*
	GRÜN* yellow RAcc = 0.779	GRÜN* green RAcc = 0.813	t_{19} = 3.502	p = 0.002*
Stim_Color$_{RAcc}$* Probe_Color$_{RAcc}$	yellow* white RAcc = 0.778	white* white RAcc = 0.796	t_{19} = 2.119	p = 0.047*
	yellow* white RAcc = 0.778	white* yellow RAcc = 0.798	t_{19} = 2.339	p = 0.030*
	yellow* white RAcc = 0.778	white* green RAcc = 0.806	t_{19} = 2.660	p = 0.015*
	yellow* white RAcc = 0.778	green* white RAcc = 0.817	t_{19} = 3.125	p = 0.006*
	yellow* yellow RAcc = 0.776	white* white RAcc = 0.796	t_{19} = 2.380	p = 0.028*
	yellow* yellow RAcc = 0.776	white* yellow RAcc = 0.798	t_{19} = 3.507	p = 0.002*
	yellow* yellow RAcc = 0.776	white* green RAcc = 0.806	t_{19} = 3.935	p = 0.001*
	yellow* yellow RAcc = 0.776	yellow* green RAcc = 0.793	t_{19} = 2.176	p = 0.042*
	yellow* yellow RAcc = 0.776	green* white RAcc = 0.817	t_{19} = 4.520	p = 0.000*
	yellow* green RAcc = 0.793	green* white RAcc = 0.817	t_{19} = 2.667	p = 0.015*
	green* yellow RAcc = 0.794	green* white RAcc = 0.817	t_{19} = 2.456	p = 0.024*
	green* green RAcc = 0.793	green* white RAcc = 0.817	t_{19} = 2.425	p = 0.025*

Table 4.3 - Significant effects in post-hoc planned comparisons in RAcc.

4.1.2 Response Time

The grand averaged response times (RT) for the congruent, incongruent and neutral stimuli are shown in Table 4.4.

20 Participants	Average	Congruent	Incongruent	Neutral
Response time (ms)	638	637	638	638
Root mean square deviation (ms)	22	22	22	22

Table 4.4 - Grand averaged response time (independent from the probe color).

In line with the analysis that was conducted on the RAcc data, a 3x3x3 repeated-measures analysis of variance (rANOVA) with the factors of *Stim_Word* (*GOLF*, *GELB*, *GRÜN*), *Stim_Color* (white, yellow, green) and *Probe_Color* (white, yellow, green) was applied to mean RT data. A trending main effect was revealed for the factor *Stim_Word* ($F_{2,38} = 3.634$, $p = 0.050$). There were no significant main effects for the factors *Stim_Color* ($F_{2,38} = 0.680$, $p = 0.505$) and *Probe_Color* ($F_{2,38} = 0.147$, $p = 0.856$). A significant *Stim_Color*Probe_Color* ($F_{4,76} = 3.459$, $p = 0.018$) interaction was observed, with other interactions showing no significant effects [*Stim_Word*Stim_Color* ($F_{4,76} = 0.180$, $p = 0.936$); *Stim_Word*Probe_Color* ($F_{4,76} = 1.010$, $p = 0.400$); *Stim_Word*Stim_Color*Probe_Color* ($F_{8,152} = 0.577$, $p = 0.742$)]. Results from this rANOVA are summarized in Table 4.5.

Main effects / Interactions	F-Value	Significance
$Stim\_Word_{RT}$	$F_{2,38} = 3.634$	$p = 0.050^{\sim}$
$Stim\_Color_{RT}$	$F_{2,38} = 0.680$	$p = 0.505$
$Probe\_Color_{RT}$	$F_{2,38} = 0.147$	$p = 0.856$
$Stim\_Word_{RT}$* $Stim\_Color_{RT}$	$F_{4,76} = 0.180$	$p = 0.936$
$Stim\_Color_{RT}$* $Probe\_Color_{RT}$	$F_{4,76} = 3.459$	$p = 0.018$*
$Stim\_Word_{RT}$* $Probe\_Color_{RT}$	$F_{4,76} = 1.010$	$p = 0.400$
$Stim\_Word_{RT}$* $Stim\_Color_{RT}$* $Probe\_Color_{RT}$	$F_{8,152} = 0.577$	$p = 0.742$

Table 4.5 - Significant effects and interactions for RT revealed by the rANOVA.

Post-hoc planned comparisons showed that the significant main effect of *Stim_Word* was driven by the factor *GELB* having a significantly faster RT than the factor *GRÜN* [*GELB*: RT = 635ms; *GRÜN*: RT = 640ms; ($t_{19} = 3.352$; $p = 0.003$)]. Significant interactions between *Stim_Color*Probe_Color* were mainly driven by the presence of

a white *Stim_Color* as compared to a yellow or green *Stim_Color*. For detailed information about the significant main effect and interactions, see Table 4.6.

Main effect/ Interactions	**Value 1**	**Value 2**	**t-Value**	**Significance**
$Stim\_Word_{RT}$	GELB RT = 635.10ms	GRÜN RT = 640.48ms	$t_{19} = 3.352$	$p = 0.003$*
$Stim\_Color_{RT}$* $Probe\_Color_{RT}$	white* yellow RT = 632.99ms	white* green RT = 642.69ms	$t_{19} = 2.979$	$p = 0.008$*
	white* yellow RT = 632.99ms	yellow* yellow RT = 641.50ms	$t_{19} = 2.306$	$p = 0.033$*
	white* yellow RT = 632.99ms	green* yellow RT = 638.32ms	$t_{19} = 2.239$	$p = 0.037$*
	green* green RT = 634.88ms	white* green RT = 642.69ms	$t_{19} = 2.172$	$p = 0.043$*

Table 4.6 - Significant effects in post-hoc planned comparisons in RT.

4.2 Neural Responses

In order to analyze the influence of congruency between word/color associations presented in the left attended VF on the neural processing of a color probe presented in the right unattended VF, the responses to the following stimuli were compared and analyzed in detail:

- Congruent vs. Incongruent vs. Neutral_match_Probe
  (to analyze whether the word/color combination would elicit a behavioral interference-related effect similar to that of the Stroop-effect and whether it would influence the neural processing of the unattended color probe)
- Neutral_match_Probe vs. Neutral_non-match_Probe
  (to analyze the influence of color information without additional semantic color information on the neural processing of the unattended color probe)

The stimuli included the following trial types:

Stimuli	**Trial types** (Left/Right Inclination already collapsed)
"Congruent"	*Stim_Word: GELB; Stim_Color:* yellow*; Probe_Color:* yellow
	Stim_Word: GRÜN; Stim_Color: green*; Probe_Color:* green
"Incongruent"	*Stim_Word: GELB; Stim_Color:* green*; Probe_Color:* green
	Stim_Word: GRÜN; Stim_Color: yellow*; Probe_Color:* yellow
"Neutral_match_Probe"	*Stim_Word: GOLF; Stim_Color:* yellow*; Probe_Color:* yellow
	Stim_Word: GOLF; Stim_Color: green*; Probe_Color:* green
"Neutral_non-match_Probe"	*Stim_Word: GOLF; Stim_Color:* yellow*; Probe_Color:* green
	Stim_Word: GOLF; Stim_Color: green*; Probe_Color:* yellow

Table 4.7 - Trial types used in subsequent analyses.

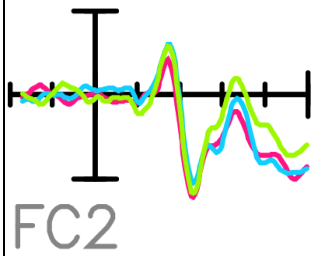
4.2.1 Responses to the Stimuli in the left, attended Visual Field

4.2.1.1 Event-Related Potential Responses

In order to determine whether the stimuli elicited a neural interference-related effect by processing the word/color combinations within the left attended VF, the grand averaged EEG waveforms of the responses to the “Congruent”, “Incongruent” and “Neutral_match_Probe” stimuli were compared. Several differences were noted across various time periods and sights. To statistically determine the presence of the effects several repeated-measures analyses of variance (rANOVAs) were conducted. For each rANOVA, the factors of *Condition* (Congruent, Incongruent, Neutral_match_Probe) and *Channels* (varying) were used. Of note, the *Channels* with similar responses were determined in an apriori manner based on visual inspection of the waveforms and as such any effects of the *Channels* are not of interest here and therefore only main effects of *Condition* are reported. The significant effects revealed by the rANOVAs were located over the frontal, fronto-central, central, central-parietal, parietal and parieto-occipital regions within the post-stimulus time of 270-1000ms (see Table 4.8/Table 4.9/Table 4.10).

Between 270-430ms, a 3x2 repeated measures analysis of variance (rANOVA) with the factors of *Condition* (Congruent, Incongruent, Neutral_match_Probe) and *Channels* (FC1, FC2) was performed revealing a significant main effect of *Condition* ($F_{2,38}$ = 4.02, p = 0.0260) in the fronto-central region. A second significant main effect of *Condition* ($F_{2,38}$ = 3.40, p = 0.0437) was observed during the same time period after performing a 3x3 repeated measures analysis of variance (rANOVA) with the factors of *Condition* (Congruent, Incongruent, Neutral_match_Probe) and *Channels* (C3, Cz, C4) over the central cortex. Furthermore, a 3x2 repeated measures analysis of variance (rANOVA) with the factors of *Condition* (Congruent, Incongruent, Neutral_match_Probe) and *Channels* (CP1, CP2) revealed a significant main effect of *Condition* ($F_{2,38}$ = 3.99, p = 0.0266) in the central-parietal region between 270-430ms. Again, within the post-stimulus time of 270-430ms, another significant main effect of *Condition* ($F_{2,38}$ = 4.88, p = 0.0130) was observed a 3x2 repeated measures analysis of variance (rANOVA) with the factors of *Condition* (Congruent, Incongruent, Neutral_match_Probe) and *Channels* (P4, PO4) over the parietal/parieto-occipital cortex.

Post-hoc planned comparisons showed that the effects were driven by the responses to the “Neutral_match_Probe” stimuli being significantly more negative than the responses to the “Congruent”/“Incongruent” stimuli, with the exception of the “Congruent vs. Neutral_match_Probe” comparison in the central region ($F_{1,19}$ = 4.19, p = 0.0547) and the “Incongruent vs. Neutral_match_Probe” comparison in the parietal/parieto-occipital region ($F_{1,19}$ = 4.37, p = 0.0502) being just trends. Table 4.8 summarizes these findings.

Electrode(s)	EEG-Wave	Time period analyzed	Main effect / specific comparison	F-Value	Significance
FC1, FC2		270-430ms	Congruent vs. Incongruent vs. Neutral_ match_Probe	$F_{2,38}$ = 4.02	p = 0.0260*
			Congruent vs. Incongruent	$F_{1,19}$ = 0.06	p = 0.8121
			Congruent vs. Neutral_ match_Probe	$F_{1,19}$ = 4.63	p = 0.0446*
			Incongruent vs. Neutral_ match_Probe	$F_{1,19}$ = 6.49	p = 0.0197*

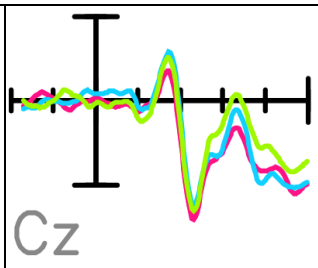
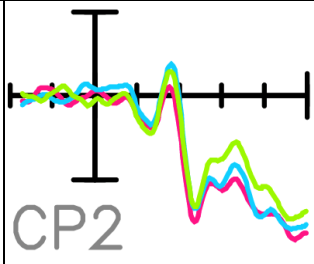
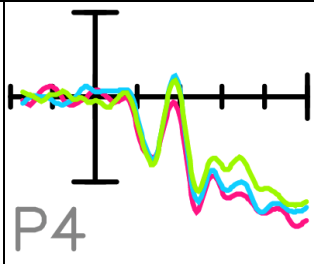
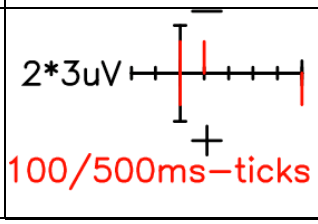
C3, Cz, C4		270-430ms	Congruent vs. Incongruent vs. Neutral_ match_Probe	$F_{2,38} = 3.40$	$p = 0.0437$*
			Congruent vs. Incongruent	$F_{1,19} = 0.13$	$p = 0.7264$
			Congruent vs. Neutral_ match_Probe	$F_{1,19} = 4.19$	$p = 0.0547$˜
			Incongruent vs. Neutral_ match_Probe	$F_{1,19} = 4.89$	$p = 0.0395$*
CP1, CP2		270-430ms	Congruent vs. Incongruent vs. Neutral_ match_Probe	$F_{2,38} = 3.99$	$p = 0.0266$*
			Congruent vs. Incongruent	$F_{1,19} = 0.49$	$p = 0.4941$
			Congruent vs. Neutral_ match_Probe	$F_{1,19} = 5.35$	$p = 0.0321$*
			Incongruent vs. Neutral_ match_Probe	$F_{1,19} = 4.42$	$p = 0.0491$*
P4, PO4		270-430ms	Congruent vs. Incongruent vs. Neutral_ match_Probe	$F_{2,38} = 4.88$	$p = 0.0130$*
			Congruent vs. Incongruent	$F_{1,19} = 1.07$	$p = 0.3137$
			Congruent vs. Neutral_ match_Probe	$F_{1,19} = 7.16$	$p = 0.0150$*
			Incongruent vs. Neutral_ match_Probe	$F_{1,19} = 4.37$	$p = 0.0502$˜
Legend:			**Congruent** **Incongruent** **Neutral_match_Probe**		**significant (*):** $p<0.05$ **trend (˜):** $0.05<p<0.10$

Table 4.8 - Significant differences between the responses to the “Neutral_match_Probe” and the “Congruent”/“Incongruent” stimuli (EEG). Grand averaged EEG data of specific electrode regions as well as their significant differences between a time interval of 270-430ms after stimulus onset.

Additionally, within the post-stimulus time window between 320-370ms, a 3x3 repeated measures analysis of variance (rANOVA) with the factors of *Condition* (Congruent, Incongruent, Neutral_match_Probe) and *Channels* (F3, Fz, F4) was performed revealing a significant main effect of *Condition* ($F_{2,38} = 3.34$, $p = 0.0462$) in the frontal region. A trending main effect of *Condition* ($F_{2,38} = 3.04$, $p = 0.0598$) was observed between 340-370ms post-stimulus by a 3x2 repeated measures analysis of variance (rANOVA) with the factors of *Condition* (Congruent, Incongruent, Neutral_match_Probe) and *Channels* (FC1, FC2) over the fronto-central cortex. Between 340-360ms, a 3x3 repeated measures analysis of variance (rANOVA) with the factors of *Condition* (Congruent, Incongruent, Neutral_match_Probe) and *Channels* (C3, Cz, C4) revealed another trending main effect of *Condition* ($F_{2,38} = 2.88$, $p = 0.0683$) in the central region.

Post-hoc planned comparisons showed that these effects were driven by the responses to the “Neutral_match_Probe” being more negative than the responses to the “Congruent” stimuli (frontal: $F_{1,19} = 4.36$, $p = 0.0414$; fronto-central: $F_{1,19} = 4.36$, $p = 0.0506$; central: $F_{1,19} = 4.24$, $p = 0.0534$) as well as by the responses to the “Incongruent” being more negative than the responses to the “Congruent” stimuli (frontal: $F_{1,19} = 3.94$, $p = 0.0618$; fronto-central: $F_{1,19} = 3.24$, $p = 0.0879$; central: $F_{1,19} = 3.06$, $p = 0.0965$). Table 4.9 summarizes these findings.

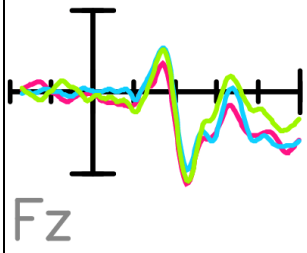
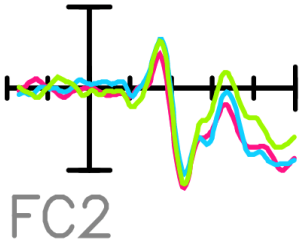
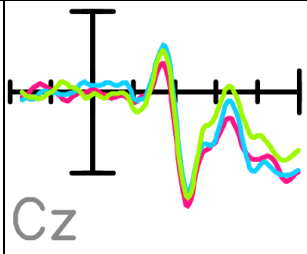
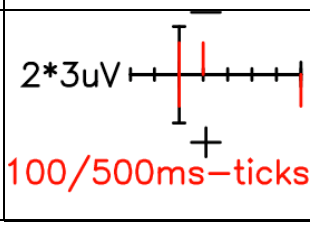
Electrode(s)	EEG-Wave	Time period analyzed	Main effect / specific comparison	F-Value	Significance
F3, Fz, F4		320-360ms	Congruent vs. Incongruent vs. Neutral_ match_Probe	$F_{2,38} = 3.34$	$p = 0.0462$*
			Congruent vs. Incongruent	$F_{1,19} = 3.94$	$p = 0.0618$˜
			Congruent vs. Neutral_ match_Probe	$F_{1,19} = 4.79$	$p = 0.0414$*
			Incongruent vs. Neutral_ match_Probe	$F_{1,19} = 1.09$	$p = 0.3099$
FC1, FC2		340-370ms	Congruent vs. Incongruent vs. Neutral_ match_Probe	$F_{2,38} = 3.04$	$p = 0.0598$˜
			Congruent vs. Incongruent	$F_{1,19} = 3.24$	$p = 0.0879$˜
			Congruent vs. Neutral_ match_Probe	$F_{1,19} = 4.36$	$p = 0.0506$˜
			Incongruent vs. Neutral_ match_Probe	$F_{1,19} = 1.21$	$p = 0.2845$
C3, Cz, C4		340-360ms	Congruent vs. Incongruent vs. Neutral_ match_Probe	$F_{2,38} = 2.88$	$p = 0.0683$˜
			Congruent vs. Incongruent	$F_{1,19} = 3.06$	$p = 0.0965$˜
			Congruent vs. Neutral_ match_Probe	$F_{1,19} = 4.24$	$p = 0.0534$˜
			Incongruent vs. Neutral_ match_Probe	$F_{1,19} = 1.23$	$p = 0.2814$
Legend:			Congruent Incongruent Neutral_match_Probe		**significant (*):** $p<0.05$ **trend (˜):** $0.05<p<0.10$

Table 4.9 - Early responses to the stimuli (EEG). Grand averaged EEG data of specific electrode regions and time periods, in which significant (main) effects or trends were found.

In the right parietal/parieto-occipital regions, contralateral to the attended VF, a significant main effect of *Condition* ($F_{2,38}$ = 3.45, p = 0.0420) was observed between 500-560ms post-stimulus after performing a 3x2 repeated measures analysis of variance (rANOVA) with the factors of *Condition* (Congruent, Incongruent, Neutral_match_Probe) and *Channels* (P4, PO4). Between 800-850ms, a 3x5 repeated measures analysis of variance (rANOVA) with the factors of *Condition* (Congruent, Incongruent, Neutral_match_Probe) and *Channels* (FC1, FC2, F3, Fz, F4) was performed revealing a significant main effect of *Condition* ($F_{2,38}$ = 3.30, p = 0.0476) in the fronto-central/frontal regions. In addition to the significant effect found between 500-560ms, a repeated measures analysis of variance (rANOVA) with the factors of *Condition* (Congruent, Incongruent, Neutral_match_Probe) revealed another significant main effect of *Condition* ($F_{2,38}$ = 4.91, p = 0.0127) in PO8 between 300-1000ms post-stimulus.

Post-hoc planned comparisons showed that these differences were driven by the responses to the “Incongruent” stimuli being significantly more negative than the responses to the “Congruent” stimuli (P4, PO4: $F_{1,19}$ = 6.80, p = 0.0173; FC1, FC2, F3, Fz, F4: $F_{1,19}$ = 10.39, p = 0.0045; PO8: $F_{1,19}$ = 19.73, p = 0.0003). Additionally, there was a trend found between the responses to the “Incongruent” and the responses to the “Neutral_match_Probe” ($F_{1,19}$ = 3.25, p = 0.0872), which likely influenced the main effect in the frontal/fronto-central regions between 800-850ms. Table 4.10 summarizes these significant differences.

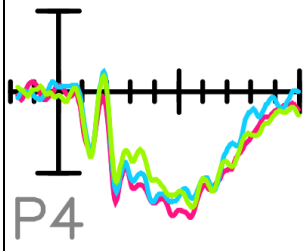
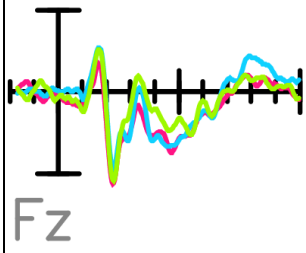
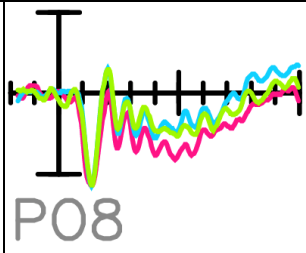
Electrode(s)	EEG-Wave	Time period analyzed	Main effect / specific comparison	F-Value	Significance
P4, PO4		500-560ms	Congruent vs. Incongruent vs. Neutral_ match_Probe	$F_{2,38} = 3.45$	$p = 0.0420$*
			Congruent vs. Incongruent	$F_{1,19} = 6.80$	$p = 0.0173$*
			Congruent vs. Neutral_ match_Probe	$F_{1,19} = 2.71$	$p = 0.1164$
			Incongruent vs. Neutral_ match_Probe	$F_{1,19} = 0.42$	$p = 0.5270$
FC1, FC2, F3, Fz, F4		800-850ms	Congruent vs. Incongruent vs. Neutral_ match_Probe	$F_{2,38} = 3.30$	$p = 0.0476$*
			Congruent vs. Incongruent	$F_{1,19} = 10.39$	$p = 0.0045$*
			Congruent vs. Neutral_ match_Probe	$F_{1,19} = 0.14$	$p = 0.7110$
			Incongruent vs. Neutral_ match_Probe	$F_{1,19} = 3.25$	$p = 0.0872$~
PO8		300-1000ms	Congruent vs. Incongruent vs. Neutral_ match_Probe	$F_{2,38} = 4.91$	$p = 0.0127$*
			Congruent vs. Incongruent	$F_{1,19} = 19.73$	$p = 0.0003$*
			Congruent vs. Neutral_ match_Probe	$F_{1,19} = 2.48$	$p = 0.1321$
			Incongruent vs. Neutral_ match_Probe	$F_{1,19} = 1.40$	$p = 0.2519$
Legend:					**significant (*):** $p<0.05$ **trend (~):** $0.05<p<0.10$

Table 4.10 - Late responses to the stimuli (EEG). Grand averaged EEG data of specific electrode regions and time periods, in which significant (main) effects were observed.

4.2.1.2 Event-Related Magnetic Field Responses

In line with the analysis of the EEG data, several repeated-measures analyses of variance (rANOVAs) were conducted in the MEG data for the factors of *Condition* (Congruent, Incongruent, Neutral_match_Probe). Between the time window of 290-850ms, several significant main effects of *Condition* were revealed by the rANOVAs.

The first significant main effect of *Condition* ($F_{2,38}$ = 4.20, p = 0.0226) was observed over the post-stimulus time window between 380-640ms. Further post-hoc planned comparisons revealed that the effect was driven by the responses to the "Neutral_match_Probe" being significantly more negative than the responses to the "Congruent" and the "Incongruent" stimuli [("Congruent" vs. "Neutral_match_Probe": $F_{1,19}$ = 4.57, p = 0.0458); ("Incongruent" vs. "Neutral_match_Probe": $F_{1,19}$ = 9.20, p = 0.0068)]. The efflux maximum was located at the sensors above the left frontal regions, whereas the influx maximum was located at the sensors above the left parietal/parieto-occipital regions. Table 4.11 summarizes these findings.

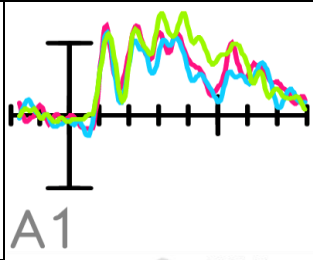
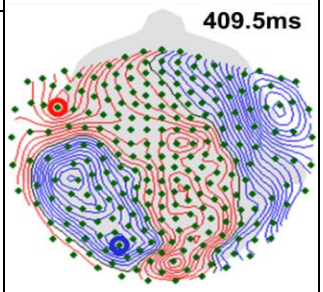
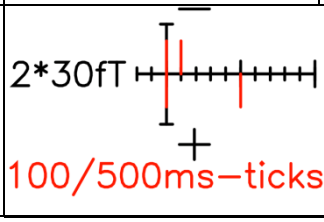
Sensors	MEG-Waves / Fieldmaps	Time period analyzed	Main effects / specific comparison	F-Value	Significance
Influx Minimum A184		380-640ms	Congruent vs. Incongruent vs. Neutral_ match_Probe	$F_{2,38}$ = 4.20	p = 0.0226*
			Congruent vs. Incongruent	$F_{1,19}$ = 0.44	p = 0.5154
Efflux Maximum A155			Congruent vs. Neutral_ match_Probe	$F_{1,19}$ = 4.57	p = 0.0458*
			Incongruent vs. Neutral_ match_Probe	$F_{1,19}$ = 9.20	p = 0.0068*
Legend:			**Congruent** **Incongruent** **Neutral_match_Probe**		**significant (*):** p<0.05 **trend (˜):** 0.05<p<0.10

Table 4.11 - Significant differences between the responses to the "Neutral_match_Probe" and the "Congruent"/"Incongruent" stimuli (MEG). Grand averaged EEG data of a significant main effect was observed between a time interval of 380-640ms after stimulus onset. The effect was located at the sensors above the left frontal and the left parietal/parieto-occipital regions.

Additionally, a second significant main effect of *Condition* ($F_{2,38}$ = 3.38, p = 0.0445) appeared in the central regions between 290-400ms post-stimulus, with the efflux maximum located above the left central region and the influx maximum located at the sensors above the right central region. Post-hoc planned comparisons showed this effect was driven by the responses to the "Congruent" stimuli being significantly more negative than the responses to the "Incongruent" and the "Neutral_match_Probe" stimuli [("Congruent" vs. "Incongruent": $F_{1,19}$ = 4.63, p = 0.0445); ("Congruent" vs. "Neutral_match_Probe": $F_{1,19}$ = 4.66, p = 0.0439)]. Table 4.12 summarizes these results.

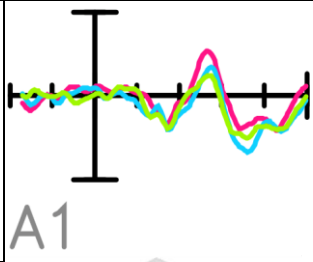
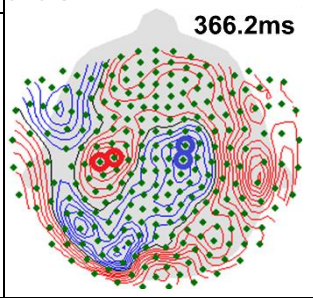
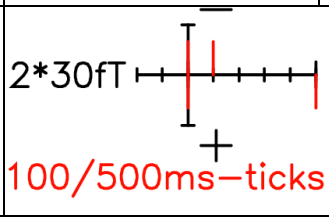
Sensors	MEG-Waves / Fieldmaps	Time period analyzed	Main effects / specific comparison	F-Value	Significance
Influx Minimum A31, A32		290-400ms	Congruent vs. Incongruent vs. Neutral_ match_Probe	$F_{2,38}$ = 3.38	p = 0.0445*
			Congruent vs. Incongruent	$F_{1,19}$ = 4.63	p = 0.0445*
Efflux Maximum A44, A69			Congruent vs. Neutral_ match_Probe	$F_{1,19}$ = 4.66	p = 0.0439*
			Incongruent vs. Neutral_ match_Probe	$F_{1,19}$ = 0.54	p = 0.4713
Legend:			**Congruent** **Incongruent** **Neutral_match_Probe**		**significant (*):** p<0.05 **trend (˜):** 0.05<p<0.10

Table 4.12 - Early responses to the stimuli (MEG). A significant main effect between the "Congruent", the "Incongruent" and the "Neutral_match_Probe" waveforms of the grand averaged data was found at the sensors above the central regions between 290-400ms post-stimulus.

Between 820-850ms, a third significant main effect of *Condition* ($F_{2,38}$ = 3.29, p = 0.0480) was observed at the sensors above the left central-parietal region (efflux maximum). However, no corresponding influx maximum was found during this time period. As was already observed between 290-400ms, post-hoc planned comparisons showed that the responses to the "Congruent" stimuli were significantly more negative than the responses to the "Incongruent" and the "Neutral_match_Probe" stimuli [("Congruent" vs. "Incongruent": $F_{1,19}$ = 4.39, p = 0.0498); ("Congruent" vs. "Neutral_match_Probe": $F_{1,19}$ = 5.18, p = 0.0346)]. Table 4.13 summarizes these results.

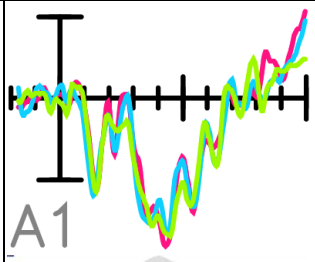
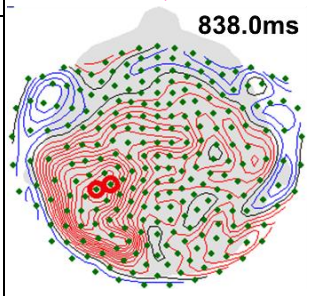
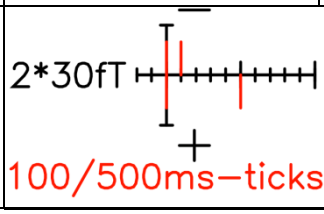
Sensors	MEG-Waves / Fieldmaps	Time period analyzed	Main effects / specific comparison	F-Value	Significance
Influx Minimum Not found		820-850ms	Congruent vs. Incongruent vs. Neutral_ match_Probe	$F_{2,38}$ = 3.29	p = 0.0480*
			Congruent vs. Incongruent	$F_{1,19}$ = 4.39	p = 0.0498*
Efflux Maximum A71, A100			Congruent vs. Neutral_ match_Probe	$F_{1,19}$ = 5.18	p = 0.0346*
			Incongruent vs. Neutral_ match_Probe	$F_{1,19}$ = 0.03	p = 0.8702
Legend:			**Congruent** **Incongruent** **Neutral_match_Probe**		**significant (*):** p<0.05 **trend (˜):** 0.05<p<0.10

Table 4.13 - Late responses to the stimuli (MEG). A significant main effect between the responses to the "Congruent", the "Incongruent" and the "Neutral_match_Probe" stimuli of the grand averaged data was observed at the sensors above the left central-parietal region between 820-850ms post-stimulus.

4.2.2 Probe-related Responses

4.2.2.1 Event-Related Potential Responses

In accordance with (Bartsch et al., 2014), the responses to the color probe, presented outside the focus of attention, were examined in electrode PO7. First, the influence of congruent and incongruent word/color combinations on the neural processing of the unattended color probe was analyzed. Therefore, waveforms across different conditions were compared over a 0-350ms post-stimulus time window as a function of whether or not the semantic content and color content of the target stimulus were congruent, incongruent, or neutral. A repeated measures analysis of variance (rANOVA) with the factors of *Condition* (Congruent, Incongruent, Neutral_match_Probe) was conducted revealing no significant main effect.

Next, the responses to the “Neutral_match_Probe” and “Neutral_non-match_Probe” stimuli were compared over the same time period. These stimuli were used, since the word *GOLF* is unrelated to color information, which excluded the neural color/color-word processing conflict. A repeated measures analysis of variance (rANOVA) with the factors of *Condition* (Neutral_match_Probe, Neutral_non-match_Probe) revealed a trending effect between 240-280ms ($F_{1,19} = 4.04$, $p = 0.0589$). The effect was driven by the responses to the “Neutral_match_Probe” stimuli being more negative than the responses to the “Neutral_non-match_Probe” stimuli. Table 4.14 summarizes these results.

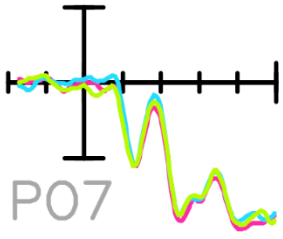
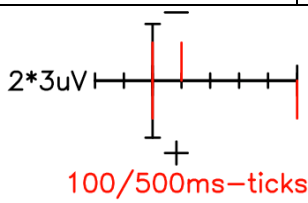
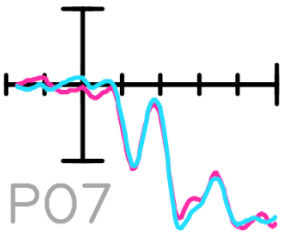
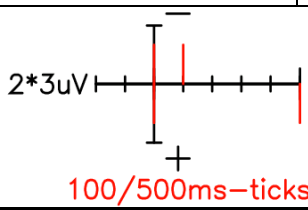
Electrode	EEG-Wave	Time period analyzed	Main effect / specific comparison	F-Value	Significance
PO7		0-350ms	Congruent vs. Incongruent vs. Neutral_ match_Probe		No significant effects found
Legend:		**Congruent** **Incongruent** **Neutral_match_Probe**			**significant (*):** $p<0.05$ **trend (˜):** $0.05<p<0.10$
PO7		240-280ms	Neutral_ match_Probe vs. Neutral_ non-match_ Probe	$F_{1,19} = 4.04$	$p = 0.0589$˜
Legend:		**Neutral_match_Probe** **Neutral_non-match_Probe**			**significant (*):** $p<0.05$ **trend (˜):** $0.05<p<0.10$

Table 4.14 - Influence of word/color associations in the neural processing of the unattended color probe (EEG). Following what had been previously done in (Bartsch et al., 2014), the responses to the stimuli of the color probe were analyzed for the grand averaged EEG data in PO7. A trend was found for the "Neutral_match_Probe" and "Neutral_non-match_Probe" stimuli between 240-280ms after stimulus onset.

4.2.2.2Event-Related Magnetic Field Responses

In line with the EEG data, a repeated measures analysis of variance (rANOVA) with the factors of *Condition* (Congruent, Incongruent, Neutral_match_Probe) was conducted in the MEG data over the 0-350ms post-stimulus time window revealing no significant effect. However, a repeated measures analysis of variance (rANOVA) with the factors of *Condition* (Neutral_match_Probe, Neutral_non-match_Probe) revealed a significant effect between 230-290ms ($F_{1,19} = 12.80$, $p = 0.0020$), with the waveform of the "Neutral_non-match_Probe" stimulus being significantly more negative than the waveform of the "Neutral_match_Probe" stimulus. Similar to the effects found in (Bartsch et al., 2014), this effect was located in the left hemisphere at

the sensors above the parietal (influx maximum) and the temporal (efflux maximum) regions. Table 4.15 summarizes these results.

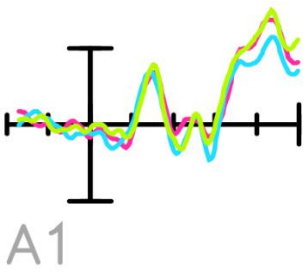
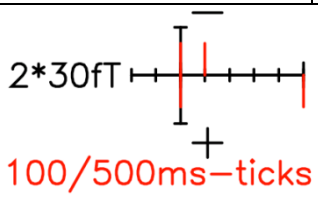
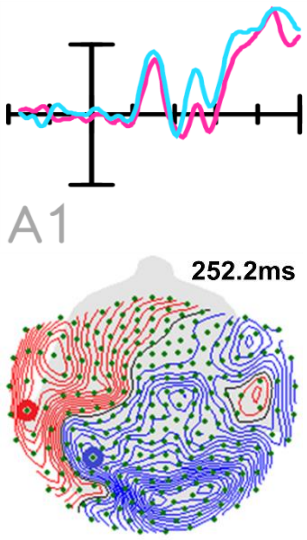
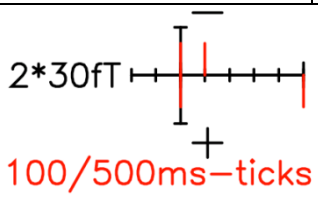
Sensors	MEG-Wave / Fieldmap	Time period analyzed	Main effect / specific comparison	F-Value	Significance
Influx Minimum A133 Efflux Maximum A197		0-350ms	Congruent vs. Incongruent vs. Neutral_ match_Probe		No significant effects found
Legend:		**Congruent** **Incongruent** **Neutral_match_Probe**			**significant (*):** p<0.05 **trend (˜):** 0.05<p<0.10
Influx Minimum A133 Efflux Maximum A197		230-290ms	Neutral_ match_Probe vs. Neutral_ non-match_ Probe	$F_{1,19}$ = 12.80	p = 0.0020*
Legend:		**Neutral_match_Probe** **Neutral_non-match_Probe**			**significant (*):** p<0.05 **trend (˜):** 0.05<p<0.10

Table 4.15 - Influence of word color associations in the neural processing of the unattended color probe (MEG). Between 230-290ms, a significant effect to the responses of the stimuli of the color probe was observed in the grand averaged MEG data at the sensors above the parietal and the temporal regions between the responses to the "Neutral_match_Probe" and "Neutral_non-match_Probe" stimuli.

5 Discussion

5.1 Interpretation of the Behavioral Data

5.1.1 Response Accuracy

Based on the findings of global feature based attention [e.g., (Zhang & Luck, 2009), (Stoppel et al., 2012)] it is known that stimuli within the unattended visual field which share a feature (e.g., the color red) with stimuli within the focus of attention will receive enhanced neural processing. However, it is still unknown whether such enhanced modulations also occur when the feature selection is influenced by semantic incongruencies of word/color combinations that are presented within the focus of attention but are task-irrelevant. In this experiment, even though the participants were instructed to simply determine the inclination of a presented word, they were influenced by the semantic meaning of the words as well as the ink color in which it was written. As seen in the behavioral response accuracy data, the participants had a significantly lower response accuracy to the non-color-word *GOLF* than to the color-words *GELB* or *GRÜN*. One possible reason for this is that participants attended the semantic meaning of the words both because of the presence of the ink colors (yellow and green) and by the relatively high ratio of color-words to non-color-words (2:1). Such a high proportion and/or priming of these color words likely captured attention more toward the words *GELB* and *GRÜN* than the color-irrelevant word *GOLF*, therefore making it easier for participants to detect the tilt of these words.

In contrast to the semantic meaning of the word, the participants showed a significantly higher response accuracy when the color of the stimulus was white or green than when it was yellow. Usually, there should not have been any differences in the response accuracy. However, these differences could be explained by the luminance of the colors and the fact that the luminance was not adjusted for each participant individually. This means that, even though five healthy, independent participants performed the flicker-test (see chapter 3.3), the luminance for yellow could be processed differently for each participant. Furthermore, it is known that

brighter, pure colors (as in this experiment e.g., white and green) receive more attention than a dulled, unsaturated color (as in this experiment e.g., yellow) (Badura, Maafi, & Kluge, 2011). For the interaction between *Stim_Word*Stim_Color*, a color/color-word processing conflict in response accuracy was observed for the color green but not for the color yellow. This means that there was a significant difference in response accuracy for the comparison (*GRÜN** green) and (*GRÜN** yellow), but not for the comparison (*GELB** yellow) and (*GELB** green). As already mentioned before, it is quite likely that the luminance of the colors is responsible for this difference and that the colors for each participant were not flickered individually.

5.1.2 Response Time

Even though the current experiment was not a Stroop-task (see also chapter 2.3), there was a similar behavioral interference-related effect (increased response time for incongruent color-word stimuli, decreased response time for congruent color-word stimuli, and an intermediate response time for neutral words) present in the pre-test (see Table 3.2). However, based on the response time of the participants (see Table 4.4), there was no behavioral interference-related effect in this experiment. For this difference, several circumstances could be responsible: First, the performance of the participants in the experiment was set much higher than in the pre-test, since a response accuracy of at least 0.75 was necessary for not being rejected. This value should determine that the participants did not just guess the inclination of the presented word and that the discrimination task was their primary attended feature. Second, the pre-test was a behaviorally test, which was recorded in a different darkened chamber than that of the experimental measurement. Therefore, the experimental settings were different (e.g., including a different projector). Additionally, the eye-movements of the participants were not recorded during the pre-test, so that trials in which participants did not maintain fixation were possibly included in the analysis.

For the interaction between *Stim_Color*Probe_Color*, the direction was not always consistent for the various stimulus color and probe color combinations. However, this difference may be also explained by the fact that the luminance was not adjusted for each participant individually.

5.2 Interpretation of the Neural Responses

5.2.1 Responses to the Stimuli in the left, attended Visual Field

Between 270-430ms (EEG data), the waveform for the responses to the neutral stimuli matching the color of the probe was significantly more negative than the waveforms for the responses to the congruent/incongruent stimuli. As seen in Table 4.8 this effect was present from the fronto-central to the right parietal/parieto-occipital cortex. Additionally to the EEG data, this significant difference could also be observed in the MEG data, appearing at sensors above the left hemisphere between 380-640ms after stimulus onset (see Table 4.11). This effect would be in line with the findings of [e.g., (Kutas & Hillyard, 1984; Kutas, Neville, & Holcomb, 1987); (Pylkkanen & Marantz, 2003)]. There it is described that around 400ms after stimulus onset (N400 component) the human brain seems to process the semantic association between the meaning of a word and the context in which it occurs. Since the word *GOLF* was non-related to any color information, it created a much larger N400 component than the color-words *GELB* or *GRÜN*, which were related to the presented colors of the experiment. These results suggest that the participants processed the words [*passive selection* (Chun & Wolfe, 2001)] and separated them into different semantic-related categories, although the meaning of the words, in contrast to [(Kutas & Hillyard, 1984; Kutas et al., 1987); (Pylkkanen & Marantz, 2003)], was completely task-irrelevant.

Furthermore, between 320-370ms post-stimulus in the EEG data and 290-400ms post-stimulus in the MEG data, several effects were observed between the waveforms of the congruent and the incongruent stimuli (see Table 4.9/Table 4.12). Interestingly, even though this experiment differed strongly to the experiments of (Liotti et al., 2000) and (Galer et al., 2014), meaning that the participants did not perform a Stroop-task, the stimuli still elicited a similar neural interference-related conflict caused by the presented color/color-word interferences. In the EEG data, the effects appeared in the same fronto-central regions as the effects in (Liotti et al., 2000), while in the MEG data, the effects were located at the sensors above the central cortex matching the sensor regions of the effects found in (Galer et al., 2014).

However, the time differences of the effects in both EEG data [effects shorter in time than in (Liotti et al., 2000)] and MEG data [effects about 90ms earlier in time than in (Galer et al., 2014)] may be explained by the different experimental tasks.

Further effects were seen in the late phase (≥ 500ms after stimulus onset) between the congruent and the incongruent waveforms (see Table 4.10/Table 4.13). Again, these effects showed similar patterns as those found by (Liotti et al., 2000) and (Galer et al., 2014), even though the present experimental task was not a Stroop-task. For example, in the EEG data, the significant differences were found in the posterior/parieto-occipital regions, as well as in the frontal/fronto-central regions as in (Liotti et al., 2000), while in the MEG data, the significant effect was located at the sensors above the central/central-parietal regions similar to those in (Galer et al., 2014). Interestingly, the waveforms did not invert, which means that the responses to the incongruent stimuli still were significantly more negative than the responses to the congruent stimuli. This pattern is in contrast to previous ERP Stroop-task studies [e.g., (Badzakova-Trajkov, Barnett, Waldie, & Kirk, 2009), (Liotti et al., 2000)], in which the congruent waveform measured at the sensors over posterior scalp regions was more negative than the incongruent waveform. This difference in results can possibly be explained by differences in experimental design, as well as the fact that the participants did not directly attend either to the semantic meaning of the word or its font color.

5.2.2 Probe-related Responses

In order to compare the results with the findings of (Bartsch et al., 2014), the neural correlates of the probe-related responses were also analyzed in electrode position PO7. The main aspect was to figure out whether congruent and incongruent word/color combinations had any influence on the neural processing of an unattended color probe. For the analyzed word/color combinations, there were no significant effects found between the congruent, the incongruent and the neutral waveforms. Based on these results, global feature-based attention seems not to be affected by semantic incongruency within the domain of color information. There are two possible explanations for this circumstance: First, the semantic information was not fully processed in time, since the semantic meaning would be processed around 400ms post-stimulus [e.g., (Kutas & Hillyard, 1984; Kutas et al., 1987); (Pylkkanen & Marantz, 2003)]. Second, too many resources were bound by the interference effect so that the color probe did not receive enhanced processing (Kandel, Schwartz, Jessell, Siegelbaum, & Hudspeth, 2012c).

The next aspect to be analyzed was whether the color of the stimuli within the focus of attention had influence on the neural processing of the color probe. To exclude the color/color-word interference, the word *GOLF*, which is non-related to any color information, was used as stimulus word. The stimuli, which were compared in order to examine the influence of color information on the neural processing of the color probe, were the responses to the neutral stimuli matching the color probe and the neutral stimuli non-matching the color of the probe. For this comparison, an effect was observed in both EEG data and MEG data (see Table 4.14/Table 4.15). Based on the amplitudes wherein the non-match condition elicited a larger amplitude, the participants needed less processing resources when the color probe outside the focus of attention matched the color of the attended task, than when it was non-matching. As has already been observed in (Bartsch et al., 2014), the significant effect in MEG data was located at the sensors above the left lateral occipito-temporal region. The fact, that the effect appeared a bit later in time may be explained due to the different experimental tasks and that the participants were not instructed to attend to a specific color here.

6 Outlook

6.1 Upcoming Steps

Unfortunately, due to a low *signal-to-noise ratio* (SNR), a source model reconstruction was not possible for the MEG data even though a promising source model was observed in the left cortex similar to that of (Bartsch et al., 2014) (see Attachment 2/3). Based on the number of trials for each participant (here: mean 21.765 trials/trial type; see also Attachment 1) and the fact that the SNR increases as a function of square root of the number of trials (Luck, 2005), the data were too noisy for most of the conditions. This means that either improbable locations or spotty effects were observed. Therefore, in order to prevent these unlikely locations and to locate the exact source for a specific effect, more data needs to be acquired.

Furthermore, a follow-up experiment would be necessary to validate the results found in this experiment. An easy way to examine the semantic conflict on global feature based attention in depth would be to exclude the inclination discrimination task while keeping the experimental design. The experiment then would be divided in two experimental tasks: in the first part, the participants would be instructed to respond as quickly as possible to the ink color of a (color)-word by pressing a button corresponding to the color (manual Stroop-task), while in the second task, the participants should respond as quickly as possible to the semantic meaning of the (color)-word by pressing a button corresponding to the semantic meaning (manual Reverse Stroop-task). Such a manipulation would mean that the color information in the experimental task would not be selected passively anymore but actively.

6.2 Conclusion

The main question was whether global feature-based attention is affected by semantic incongruency (within the domain of color information). Therefore, the influence of semantic incongruency on the neural processing of a color probe presented outside the focus of attention was examined by using congruent and incongruent word/color combinations in the attended visual field. Even though the

semantic meaning of the word/color combinations was completely task-irrelevant for the experimental task, the participants showed several neural and behavioral interference-related effects. Furthermore, an effect (N400 component), which seems to be related to the processing of the meaning of a word and to the context in which it occurs, was observed. Analyzing the responses to the unattended color probe showed that the perceptual-semantic incongruence of word/color combinations had no influence on the neural processing of the color probe. However, for colored stimuli without semantic color information presented within the focus of attention, the color probe in the unattended visual field elicited enhanced modulations of electromagnetic potentials in the contralateral visual cortex for the non-matching condition (color of the stimuli did not match the color of the probe) as compared to the matching condition (color of the stimuli matched the color of the probe). These results suggest that either the semantic information was not fully processed to show an effect on global feature-based attention or that too many attentional resources were needed to process the interference-related effect so that features outside the focus of attention were not further attended/processed.

7 References

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Acknowledgement

First of all I would like to especially thank Prof. Dr. Mircea Ariel Schoenfeld for supervising this Master thesis, for supporting me throughout as well as for reviewing my thesis.

Secondly, a special thanks to Dr. Sarah Donohue for her great support in the fields of global vision and the Stroop-effect, her patience in answering all my questions as well as for reviewing my thesis.

Furthermore, I would like to thank Dr. Mandy Bartsch for her support in the field of global vision and for answering all my questions.

Moreover, special thanks to my colleagues Dr. Joseph Harris and Dipl.-Biol. Steffi Weinhold for supporting me in the use of different programs as well as for answering all my questions.

Additionally, great thanks to Laura Herrmann and Steffi Bachmann for their help and support during the experimental task.

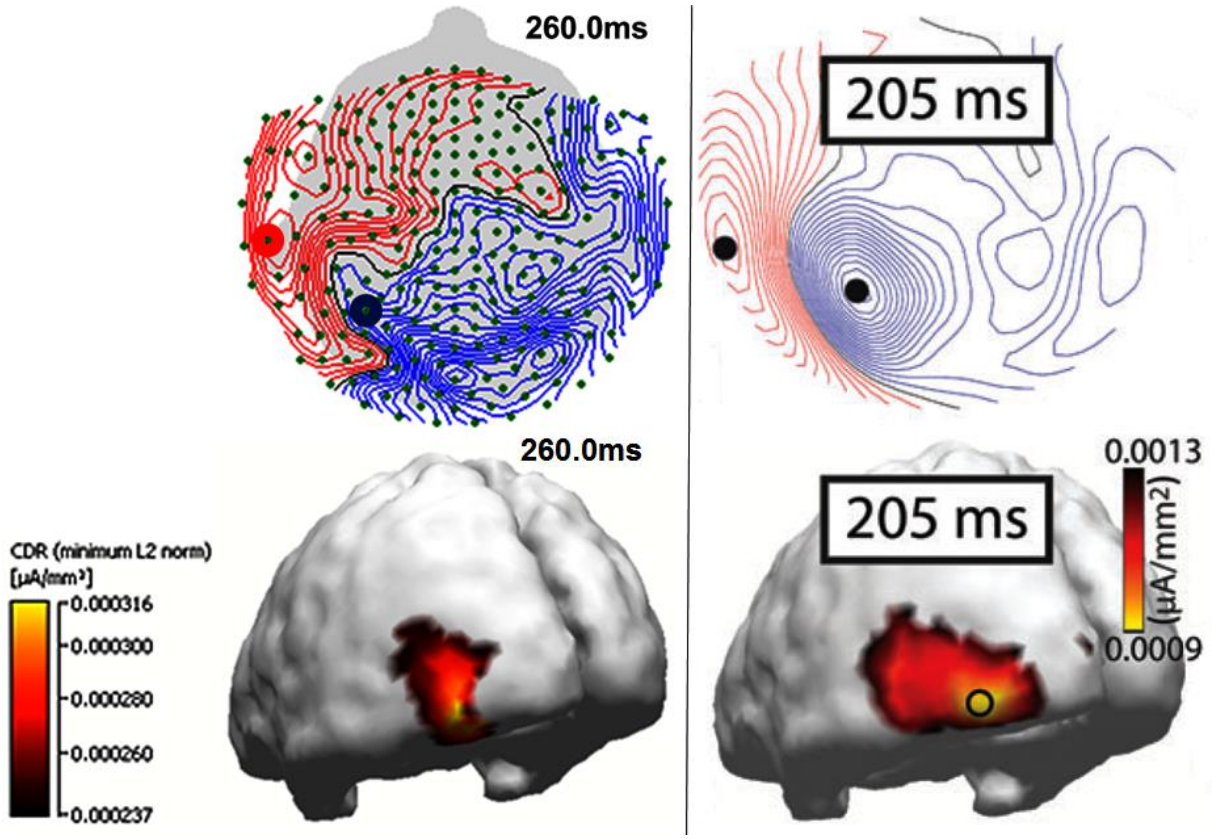
Finally, I want to thank my parents and my girlfriend Kirsten, who supported and encouraged me throughout my thesis.

I cordially thank you for the wonderful time together!

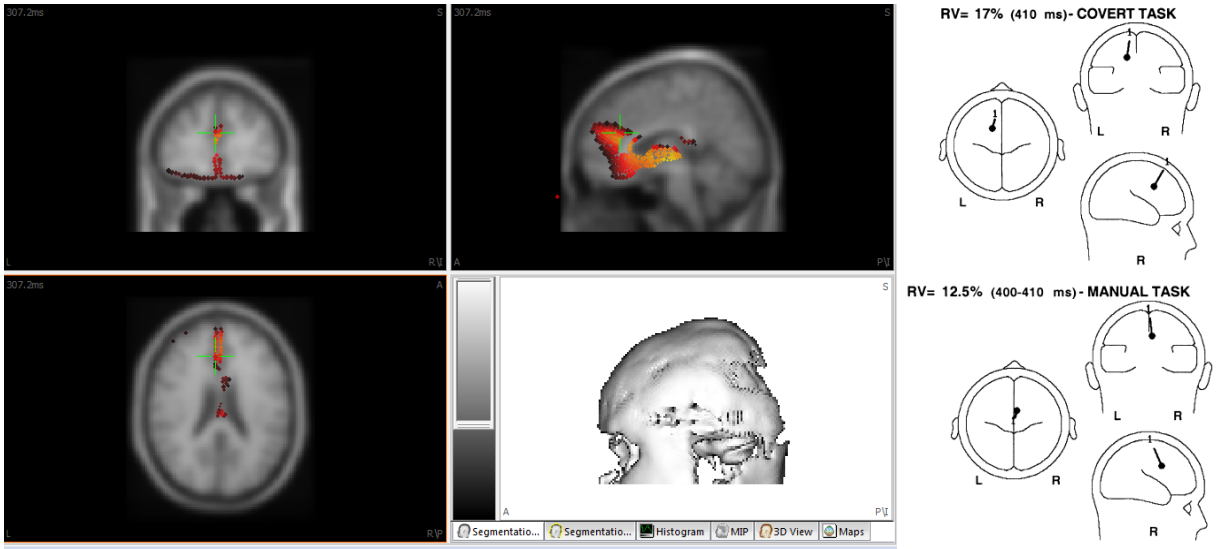
Attachments

EEG	bd53	ho33	so70	tt42	kl93	bx95	lr92	zf01	tg08	ac49	jr31	sc17	jv60	ic49	gm48	ox81	yx15	kt10	gu16	hl97	Total Hit-Rate
Bin 1-2	40	42	42	47	45	46	38	40	34	36	33	41	33	42	41	47	41	40	37	47	(of max. 60)
Bin 3-4	49	42	51	49	46	44	42	44	36	27	37	42	38	42	43	46	37	30	34	44	
Bin 5-6	34	38	49	52	45	46	44	42	44	27	39	45	37	38	43	42	40	28	41	45	
Bin 7-8	46	48	48	50	42	43	44	42	44	38	39	48	37	48	43	51	43	30	43	46	
Bin 9-10	48	36	50	49	49	47	41	48	42	46	38	48	38	36	45	47	36	31	49	45	
Bin 11-12	49	43	45	49	50	52	46	43	43	44	38	51	35	43	43	42	44	32	46	45	
Bin 13-14	42	44	50	46	47	48	42	39	42	44	41	46	40	44	40	41	34	34	44	48	
Bin 15-16	42	44	44	47	44	51	34	41	43	39	33	47	37	44	37	38	41	33	41	42	
Bin 17-18	38	44	46	49	45	46	42	47	47	44	37	45	35	44	40	42	41	37	40	42	
Bin 19-20	48	45	47	41	41	47	37	46	37	35	32	43	34	45	41	46	39	27	50	48	
Bin 21-22	42	45	44	45	40	44	35	48	42	29	40	46	31	45	40	47	41	34	46	43	
Bin 23-24	47	47	46	49	48	48	38	39	38	43	35	38	31	47	40	41	43	30	42	43	
Bin 25-26	41	44	44	48	49	51	43	42	36	43	34	50	33	44	45	42	37	29	40	42	
Bin 27-28	42	47	50	45	48	48	38	44	38	38	28	49	39	47	46	42	45	28	38	48	
Bin 29-30	45	44	50	44	40	48	38	49	51	40	36	48	43	44	44	42	36	35	41	45	
Bin 31-32	46	41	45	47	46	45	39	36	33	35	35	46	28	41	45	43	39	34	42	41	
Bin 33-34	43	46	43	53	47	46	35	40	38	38	45	45	37	46	40	39	41	33	40	40	
Bin 35-36	38	45	52	51	46	34	40	46	43	41	38	49	32	45	43	42	39	29	47	48	
Bin 37-38	40	42	52	46	49	49	43	50	37	34	41	44	38	42	41	45	44	30	44	43	
Bin 39-40	40	43	56	43	45	45	39	41	38	34	43	49	42	43	37	50	44	31	42	44	
Bin 41-42	43	42	53	51	43	43	36	44	41	42	46	46	34	42	47	43	32	37	39	43	
Bin 43-44	41	44	47	48	38	50	37	48	41	38	36	51	40	44	39	45	46	35	38	43	
Bin 45-46	39	48	48	49	47	46	39	44	43	41	38	47	35	48	43	43	38	35	42	41	
Bin 47-48	42	41	47	44	42	47	36	52	41	40	38	47	39	41	41	48	46	34	42	39	
Bin 49-50	46	51	51	49	43	47	44	50	50	43	46	46	44	51	43	43	36	36	39	48	
Bin 51-52	41	48	47	52	54	47	42	45	38	38	42	43	34	48	46	46	35	31	47	50	
Bin 53-54	42	39	43	43	42	39	39	51	41	33	39	42	42	39	41	47	42	36	40	37	
Avg EEG	42.74	43.81	47.78	47.63	45.22	46.19	39.67	44.48	40.78	38.15	38.04	46.00	36.52	43.81	42.11	44.07	40.00	32.56	42.00	44.07	42.28
Before ArtRej	47.89	48.74	52.56	48.63	50.15	50.19	48.44	46.52	51.08	48.63	48.59	49.37	43.78	46.04	45.26	50.85	44.74	42.26	44.48	45.15	47.67
ArtRej (%)	10.75	10.11	9.09	2.06	9.82	7.97	18.12	4.38	20.16	21.55	21.72	6.82	16.58	4.83	6.96	13.33	10.59	22.96	5.57	2.39	11.30
SD (%)																					1.50
MEG																					
Bin 1-2	42	42	43	45	49	42	37	41	43	40	35	44	42	42	41	51	46	39	37	41	
Bin 3-4	50	36	51	47	48	41	38	49	45	32	42	44	42	36	44	49	43	32	37	41	
Bin 5-6	40	36	48	51	49	47	47	42	51	33	42	42	45	36	46	46	42	31	39	38	
Bin 7-8	47	48	49	45	47	41	43	43	50	40	39	50	41	48	46	51	46	34	43	41	
Bin 9-10	51	40	51	44	49	46	40	48	50	45	42	51	41	40	46	46	41	29	51	43	
Bin 11-12	48	42	49	48	52	51	39	45	47	46	41	51	42	42	45	40	47	34	48	42	
Bin 13-14	48	42	53	45	50	47	41	42	46	49	45	46	47	42	47	42	40	37	46	46	
Bin 15-16	44	45	50	44	47	51	34	46	46	46	38	47	42	45	42	37	44	33	45	39	
Bin 17-18	39	45	47	45	42	43	42	47	45	45	41	48	46	45	43	44	47	38	41	36	
Bin 19-20	49	48	47	39	42	45	36	45	35	40	37	48	40	48	42	46	46	29	50	42	
Bin 21-22	46	45	49	45	40	43	31	51	44	35	41	46	39	45	43	49	44	34	48	41	
Bin 23-24	45	46	48	46	48	47	35	43	43	48	37	40	37	46	45	42	46	28	43	42	
Bin 25-26	46	44	45	48	48	46	39	43	43	47	37	50	39	44	47	42	41	32	42	38	
Bin 27-28	44	44	51	44	49	47	36	43	41	39	32	49	45	44	46	40	45	29	41	38	
Bin 29-30	51	42	54	45	42	48	37	47	51	44	39	48	47	42	46	41	41	33	41	42	
Bin 31-32	49	42	41	43	47	46	42	40	43	39	38	48	34	42	48	45	42	34	43	42	
Bin 33-34	46	44	44	48	49	45	36	41	44	44	47	46	42	44	40	41	44	32	40	38	
Bin 35-36	38	45	55	47	52	33	40	48	48	46	41	51	35	45	45	45	47	28	49	43	
Bin 37-38	45	42	52	43	50	48	41	53	44	42	43	43	41	42	43	45	53	31	45	36	
Bin 39-40	48	35	54	40	50	46	36	41	44	39	42	49	43	35	41	50	46	32	42	38	
Bin 41-42	47	37	51	48	44	40	34	43	46	44	49	48	38	37	47	46	36	35	40	43	
Bin 43-44	43	44	49	45	40	51	32	49	45	40	39	50	44	44	45	43	51	33	40	41	
Bin 45-46	40	48	49	49	49	46	35	46	51	43	40	46	39	48	43	44	42	39	42	33	
Bin 47-48	44	40	50	43	45	47	32	53	52	45	43	47	46	40	44	47	48	31	44	36	
Bin 49-50	47	52	56	46	47	47	43	52	52	50	48	46	46	52	47	46	44	38	40	44	
Bin 51-52	47	42	48	51	56	51	38	45	44	41	44	46	41	42	49	46	37	35	49	46	
Bin 53-54	44	42	41	42	48	40	36	52	47	42	45	43	48	42	43	46	47	37	42	35	
Avg MEG	45.48	42.89	49.07	45.41	47.37	45.37	37.78	45.85	45.93	42.37	41.00	46.93	41.93	42.89	44.59	44.81	44.30	33.22	43.26	40.19	43.53
Before ArtRej	47.89	48.74	52.56	48.63	50.15	50.19	48.44	46.52	51.08	48.63	48.59	49.37	43.78	46.04	45.26	50.85	44.74	42.26	44.48	45.15	47.67
ArtRej (%)	5.02	12.00	6.63	6.63	5.54	9.59	22.02	1.43	10.08	12.86	15.62	4.95	4.23	6.84	1.47	11.87	0.99	21.38	2.74	11.00	8.67
SD (%)																					1.36

Attachment 1 - Detailed information about the rejected epochs.



Attachment 2 - Fieldmaps and Source models of the Color Probe-related Responses during this experiment (left) and (Bartsch et al., 2014) (right).



Attachment 3 - Source models of the interference-related effects. Interference-related Effects (incongruent minus congruent) caused by the Stimuli in the left, attended Visual Field 307.2ms after stimulus onset (left). As seen, the effects appear about 100ms earlier but only partially in the same region as observed by (Liotti et al., 2000) (right; the anterior cingulate cortex). However, due to a low signal-to-noise ratio, additional locations were observed in non-plausible sources such as the ventricles.